Overview of PDFs in the LHC era

What are the challenges & opportunities

Fred Olness
SMU

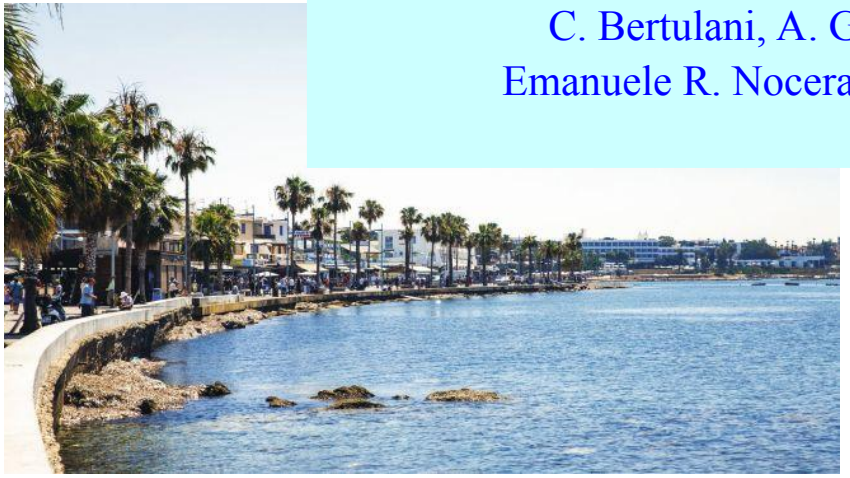
nCTEQ
nuclear parton distribution functions

Thanks to my nCTEQ colleagues
B. Clark, E. Godat, T. Hobbs, T. Jezo, C. Keppel, A. Kusina, F. Lyonnet,
J.G. Morfin, M. Klasen, K. Kovarik, J.F. Owens, I. Schienbein, J.Y. Yu

and my xFitter colleagues
V. Bertone, M. Botje, D. Britzger, S. Camarda, A. Cooper-Sarkar, F. Giuli,
A. Glazov, A. Luszczak, R. Placakyte, V. Radescu, W. Slominksi, O. Zenaiev

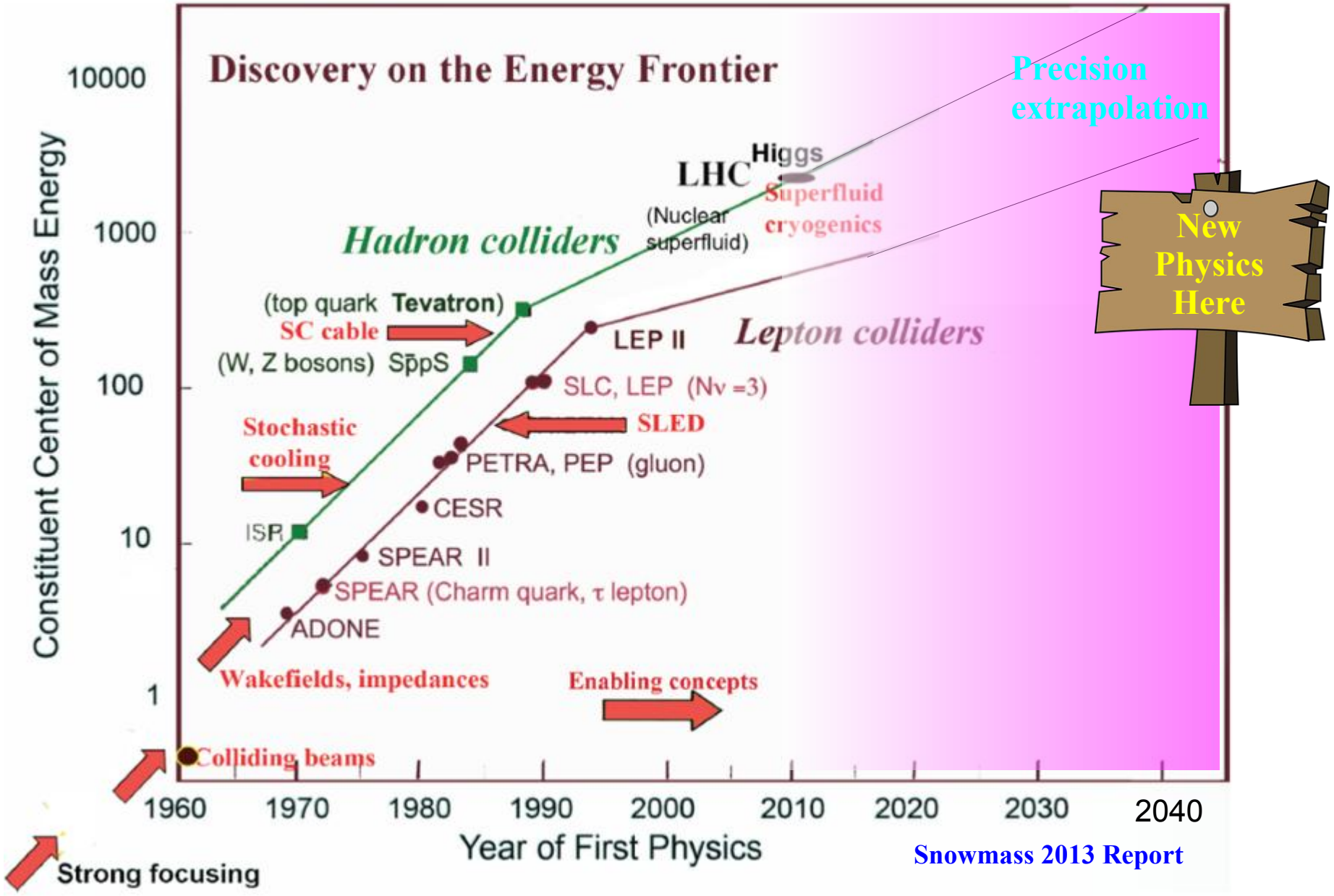
and also
C. Bertulani, A. Geiser, C. Gwenlan, M. Guzzi, P. Nadolsky,
Emanuele R. Nocera, Huey-Wen Lin, Kostas Orginos, Juan Rojo

xFitter



EINN 2019 European Research Conference
Electromagnetic Interactions with Nucleons and Nuclei
27 Oct -- 2 Nov 2019: Paphos, Cyprus

Opportunity: Landscape of the Energy Frontier



We've reached the peak energy. **Future searches require precision!!!**

FCC options are on a different time scale

Measurements of Drell-Yan cross sections at 13 TeV with CMS

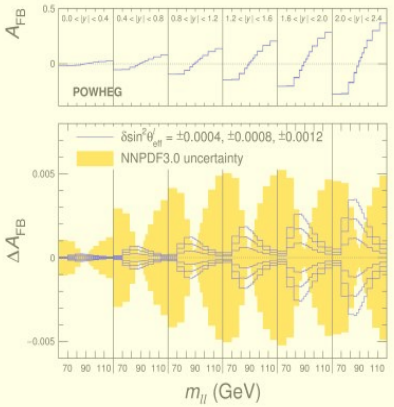
James Stirling Memorial Conference
September, 2019

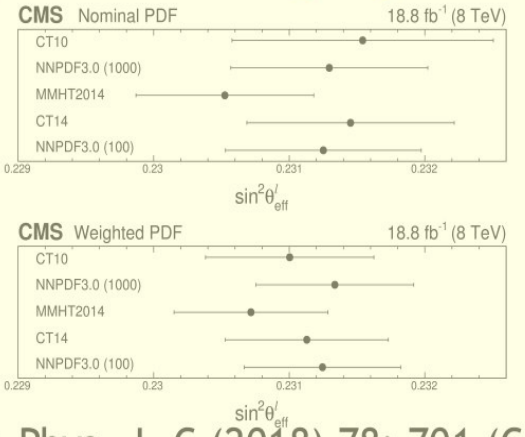
Aram Apyan
For the CMS Collabora

... for example ...

Introduction

- PDF's are an important or dominant uncertainty to precision measurements at the LHC (e.g. $\sin^2\theta_W$ and W mass)
- Measurements of W and Z production at the LHC can constrain PDFs in the relevant phase space
  - In-situ constraints can also be used to constrain PDFs in the context of the measurements themselves (e.g. CMS weak mixing angle measurement)





Eur. Phys. J. C (2018) 78: 701 (CMS)

- Purpose of this talk is to show a short summary on the differential Drel-Yan cross section measurements using dilepton events in CMS with 13 TeV

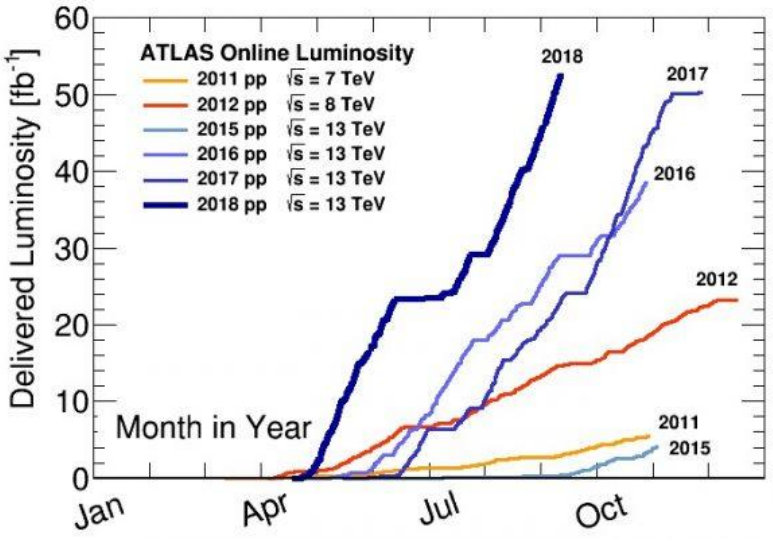
The Key to Understanding: The Parton Model and Factorization

$$\sigma_{N\gamma\to c} = f_{N\to a} \otimes \hat{\sigma}_{a\gamma\to c}$$

Experimental Observables

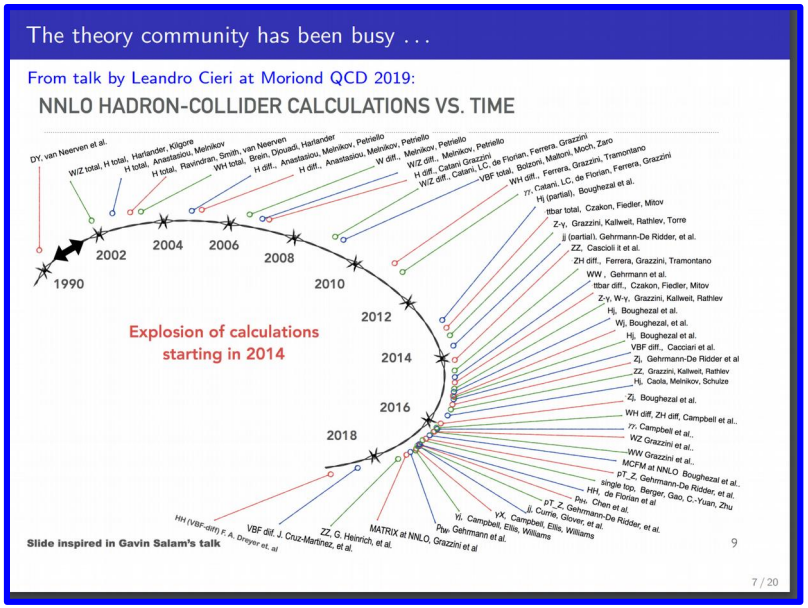
WHAT ABOUT PDF'S ???

Theoretical Calculations



Andrei Gritsan

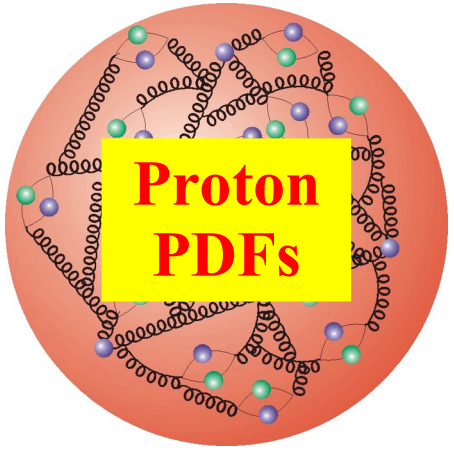
?

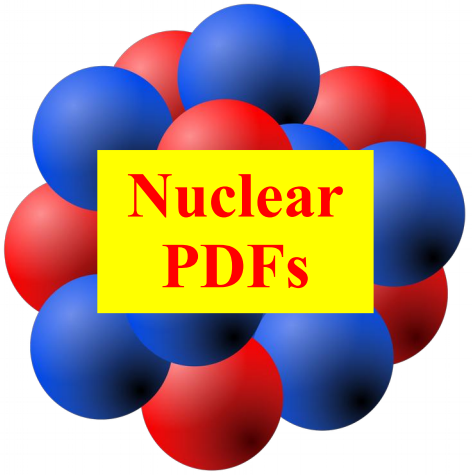


Doreen Wackeroth

" PDF uncertainties are among the leading uncertainties in the first LHC precision measurements by CMS" *Jan Kretzschmar*

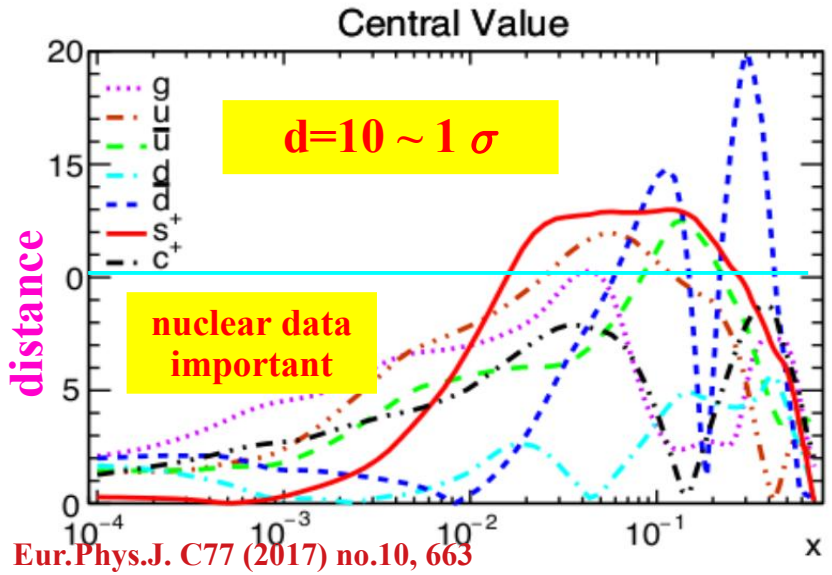
Why do proton PDFs depend on nuclear data





Impact of Nuclear Data on Flavor Decomposition

NNPDF3.1 NNLO, Impact of nuclear+deuteron fixed-target data , Q = 100 GeV



Eur.Phys.J. C77 (2017) no.10, 663

$$F_2^{\nu} \sim \left[d + s + \bar{u} + \bar{c}\right]$$

$$F_2^{\bar{\nu}} \sim \left[\bar{d} + \bar{s} + u + c\right]$$

$$F_3^{\nu} = 2\left[d + s - \bar{u} - \bar{c}\right]$$

$$F_3^{\bar{\nu}} = 2\left[u + c - \bar{d} - \bar{s}\right]$$

Extraction of Proton PDF flavors is inextricably linked to the nuclear degrees of freedom

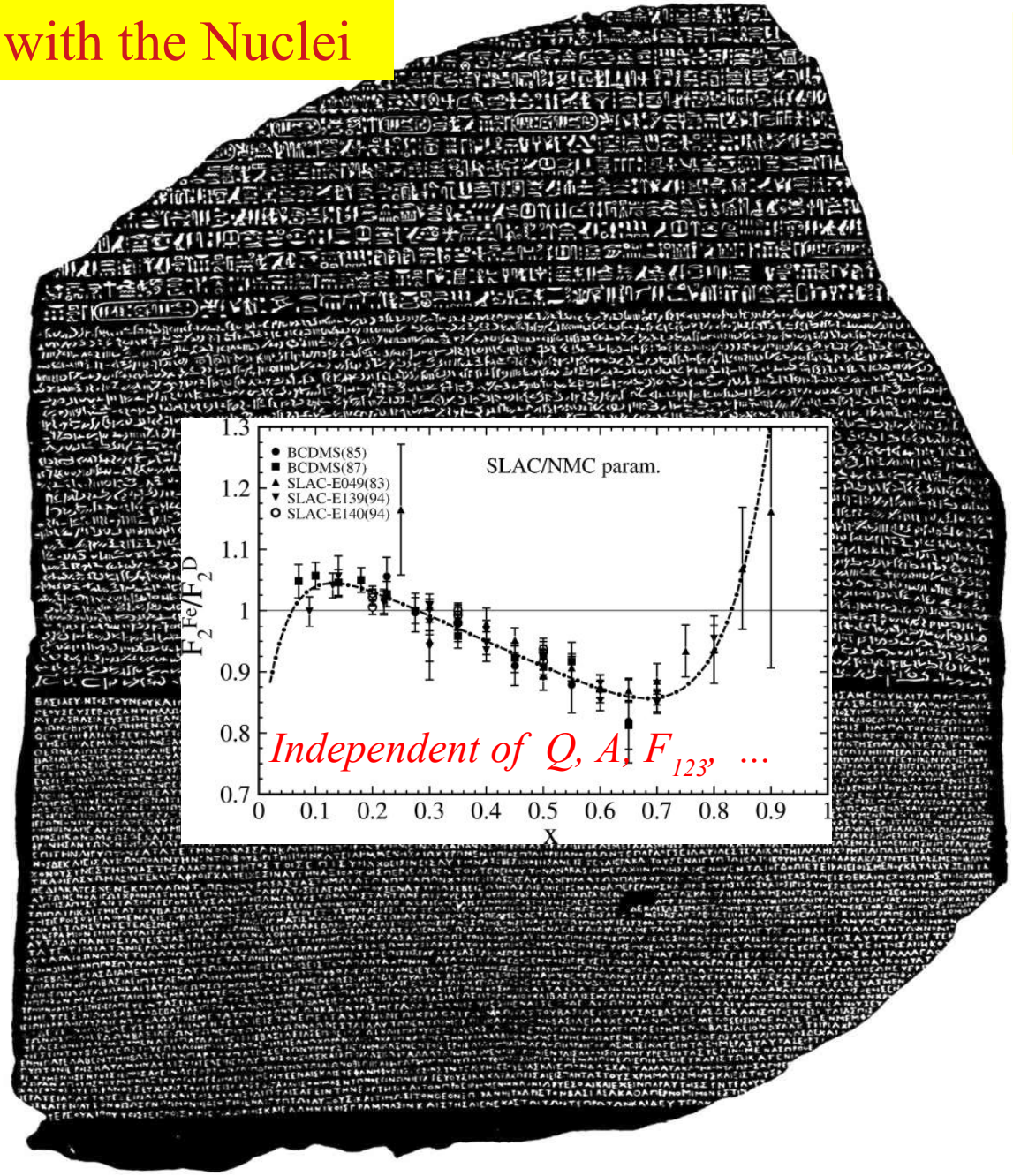
Eur.Phys.J. C77 (2017) no.10, 663

Giele, Keller, Kosower

Where do nuclear correction factors come from???

Where do nuclear corrections come from ????

We need to deal with the Nuclei

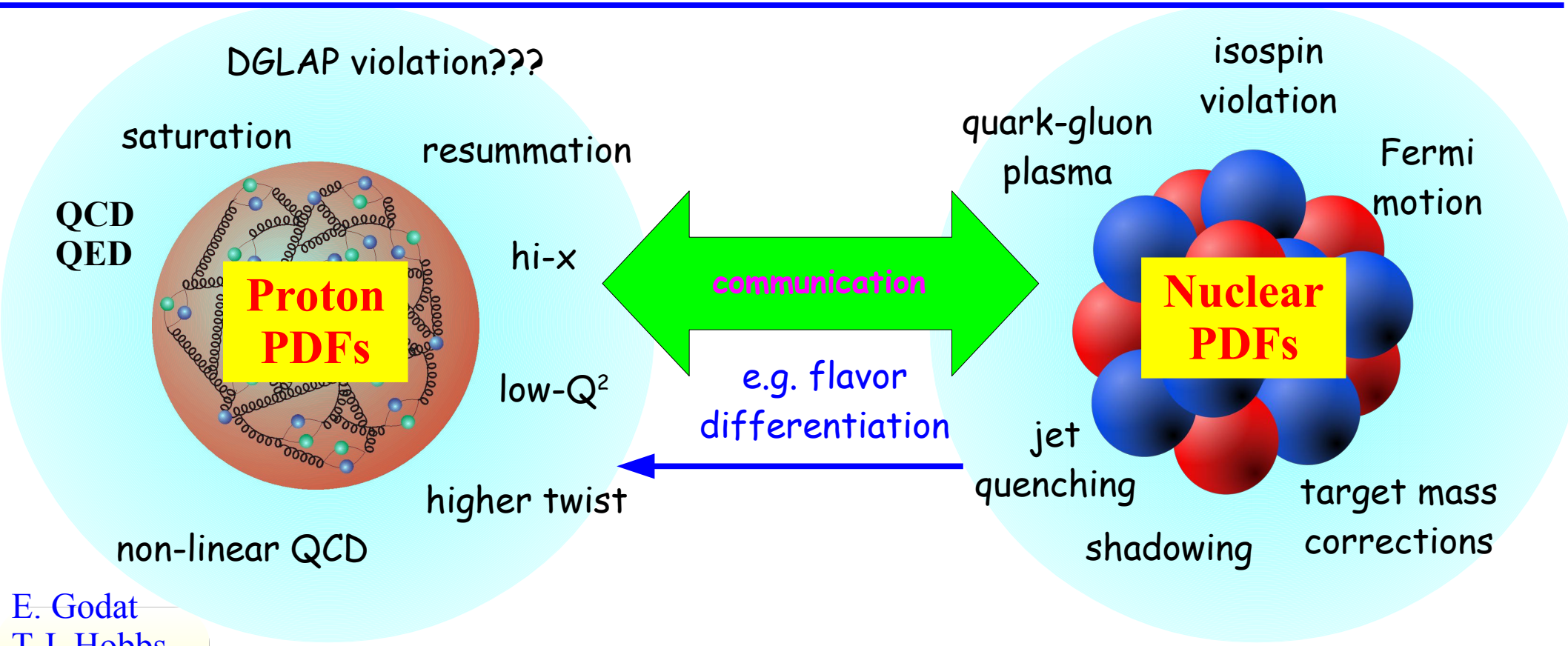


The ratio of iron (Fe) to Deuterium (D)

$$\frac{F_2^{Fe}}{F_2^D}$$

Discovered by the French in 1799 at Rosetta, a harbor on the Mediterranean coast in Egypt. Comparative translation of the stone assisted in understanding many previously undecipherable examples of hieroglyphics.

… the motivation for nCTEQ



E. Godat
T.J. Hobbs
T. Jezo,
C. Keppel,
M. Klasen
K. Kovarik
A Kusina,
F. Lyonnet,
J. Morfin,
F. Olness
J. Owens,
I. Schienbein,
J. Yu

Data from nuclear targets play a key role in the flavor differentiation

nCTEQ

nuclear parton distribution functions

THE CAST

HKN

DSSZ

EPS & EPPS

nCTEQ

NNPDF

TUJU

Nuclear PDFs: Data sets & cuts for nPDF fits

NC DIS & DY

SLAC E-139 & E-049
N = (D, Ag, Al, Au, Be,C, Ca, Fe, He)

CERN BCDMS & EMC & NMC
N = (D, Al, Be, C, Ca, Cu, Fe, Li, Pb, Sn, W)

DESY Hermes
N = (D, He, N, Kr)

FNAL E-665
N = (D, C, Ca, Pb, Xe)

FNAL E-772 & E-886
N = (D, C, Ca, Fe,W)

Neutrino DIS*

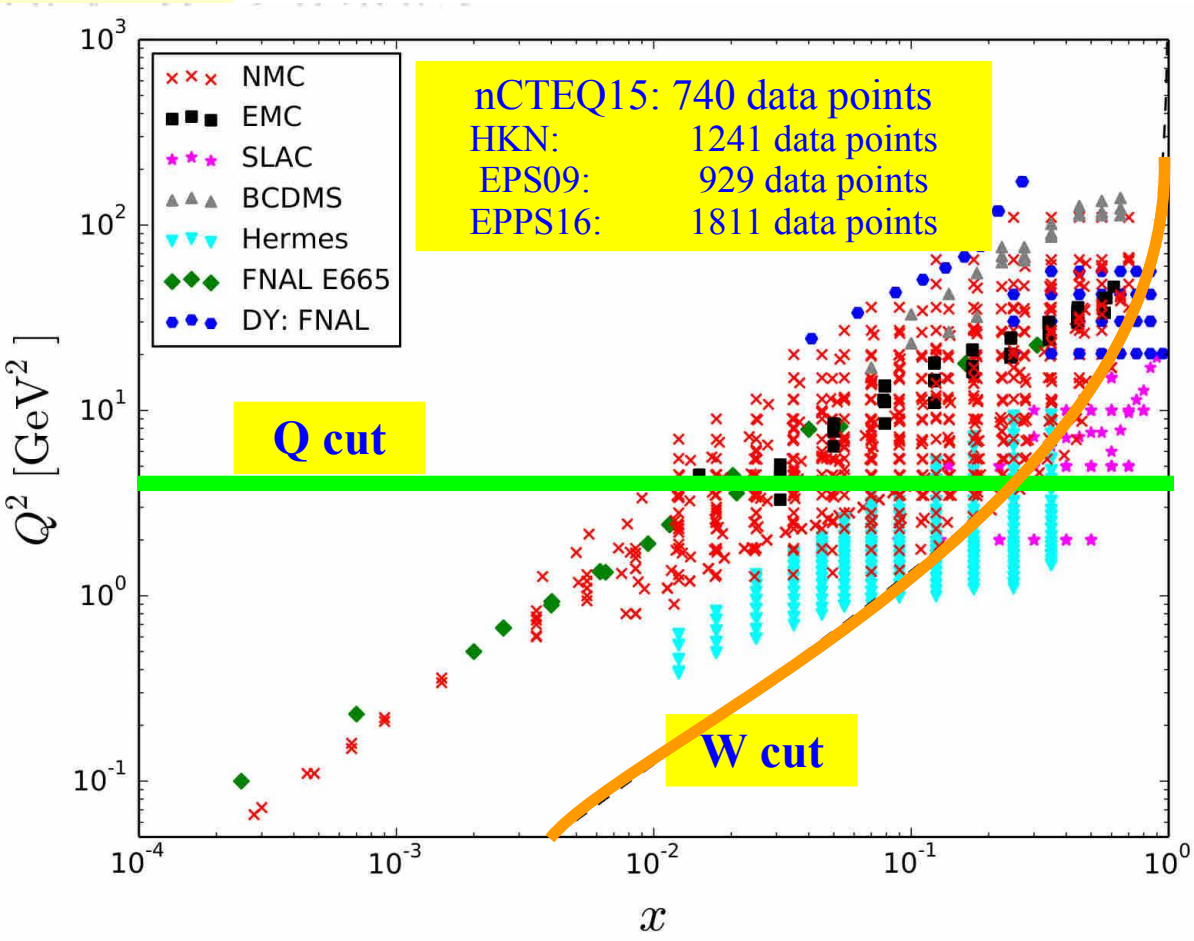
NuTeV CHORUS CCFR & NuTeV
N = Pb & Fe

Pion Production:

RHIC: PHENIX & STAR
N = Au

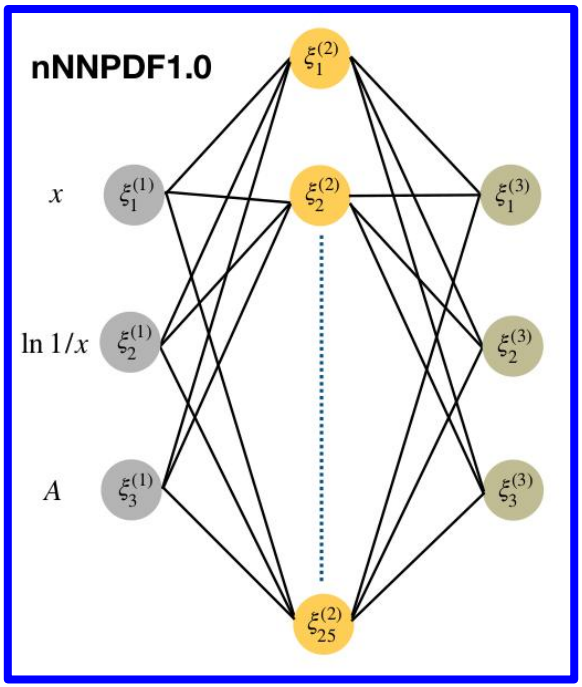
will show comparision w/ LHC pPb

DIS Cuts:
nCTEQ: Q>2.0 & W>3.5
EPPS16: Q>2.0 & W>3.5
EPS09: Q>1.3
HKN: Q>1.0
DSSZ: Q>1.0



proton vs nuclear: fewer data and more DOF ... impose assumptions on nPDFs

NNPDF Nuclear PDFs

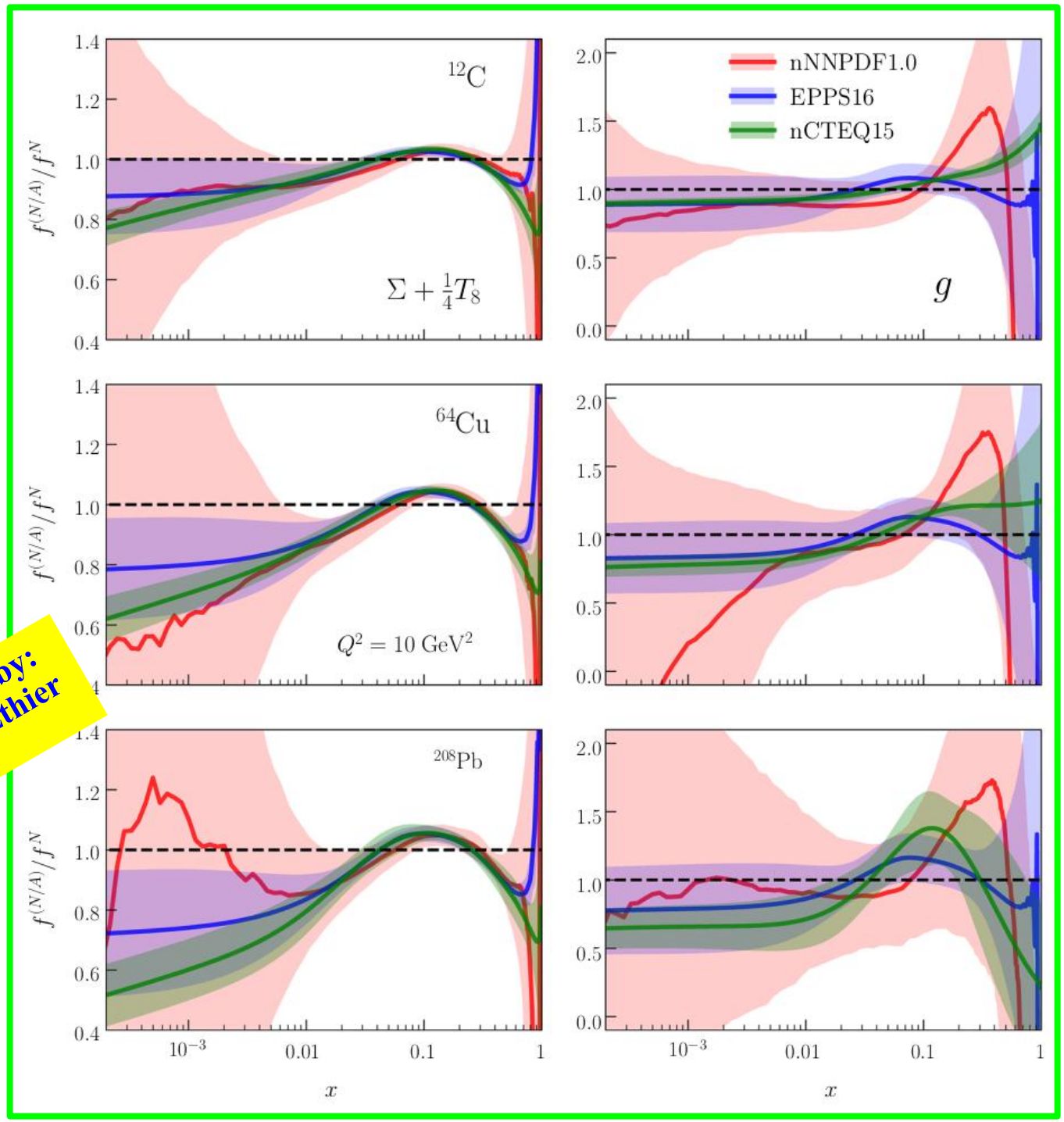


$$g(x, Q_0, A) = B_g x^{-\alpha_g}(1-x)^{\beta_g}\,\xi_1^{(3)}$$

$$\Sigma(x, Q_0, A) = x^{-\alpha_\Sigma}(1-x)^{\beta_\Sigma}\,\xi_2^{(3)}$$

$$T_8(x, Q_0, A) = x^{-\alpha_{T_8}}(1-x)^{\beta_{T_8}}\,\xi_3^{(3)}$$

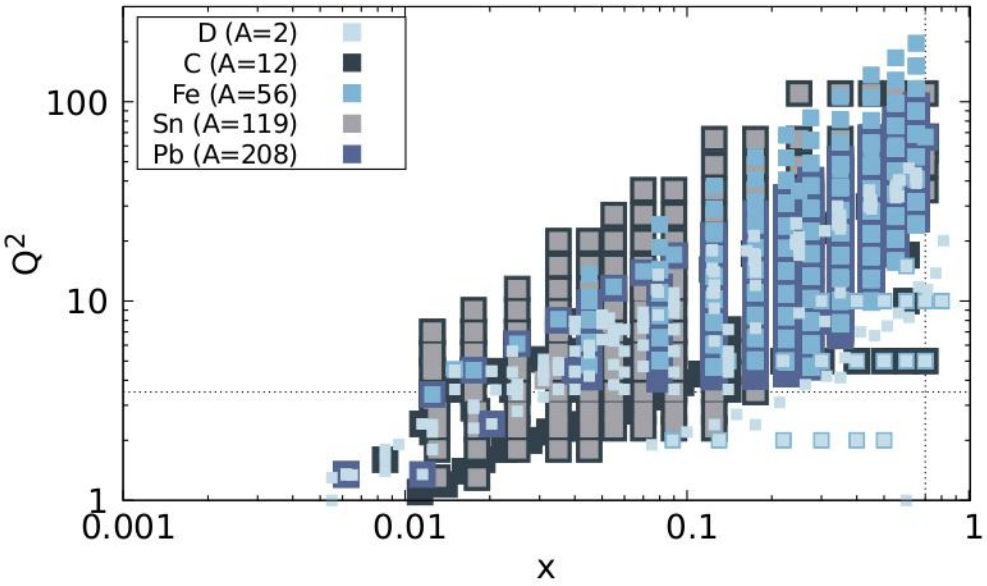
See talk by: Jacob Ethier

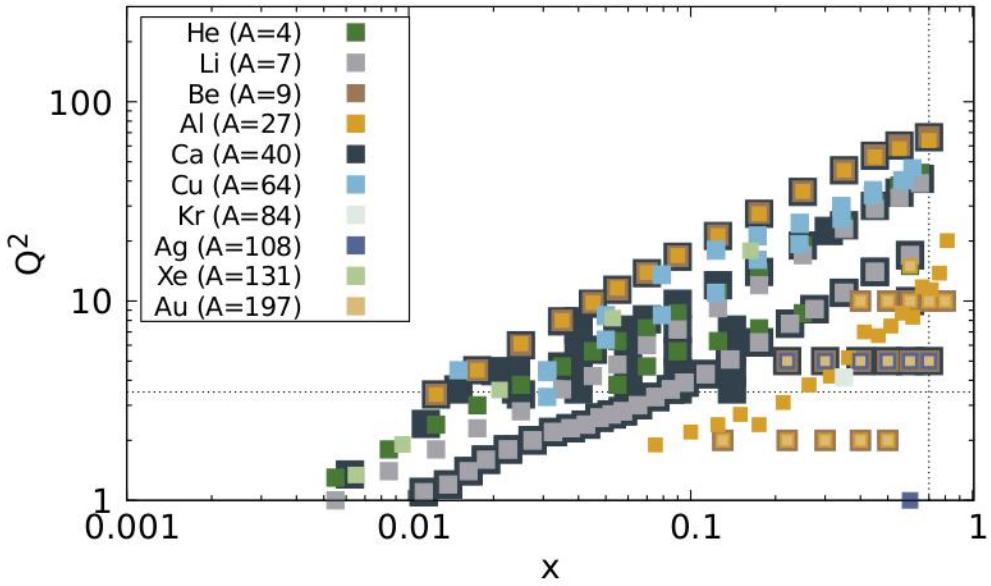


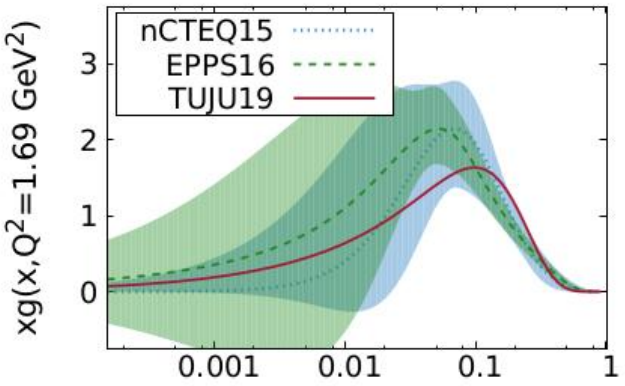
NNPDF Collaboration: Rabah Abdul Khalek, Jacob J. Ethier, Juan Rojo
Eur. Phys. J. C (2019) 79:471

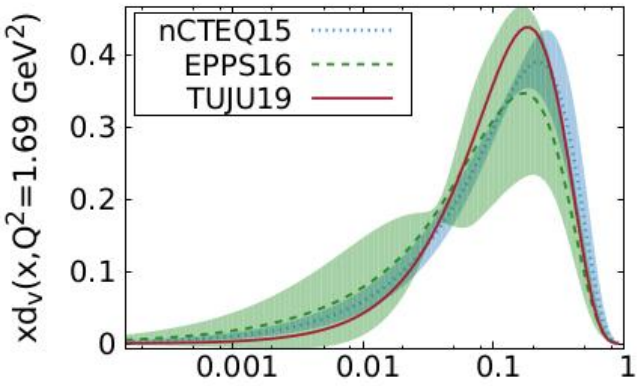
TUJU19 nPDFs at NLO & NNLO: … *xFitter*

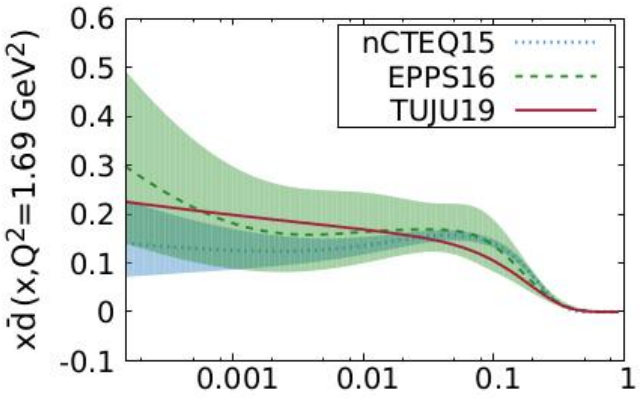
Open-source QCD analysis of nuclear parton distribution Functions at NLO and NNLO
Institute for Theoretical Physics, University of **Tübingen**, University of **Jyväskylä**, (TUJU)





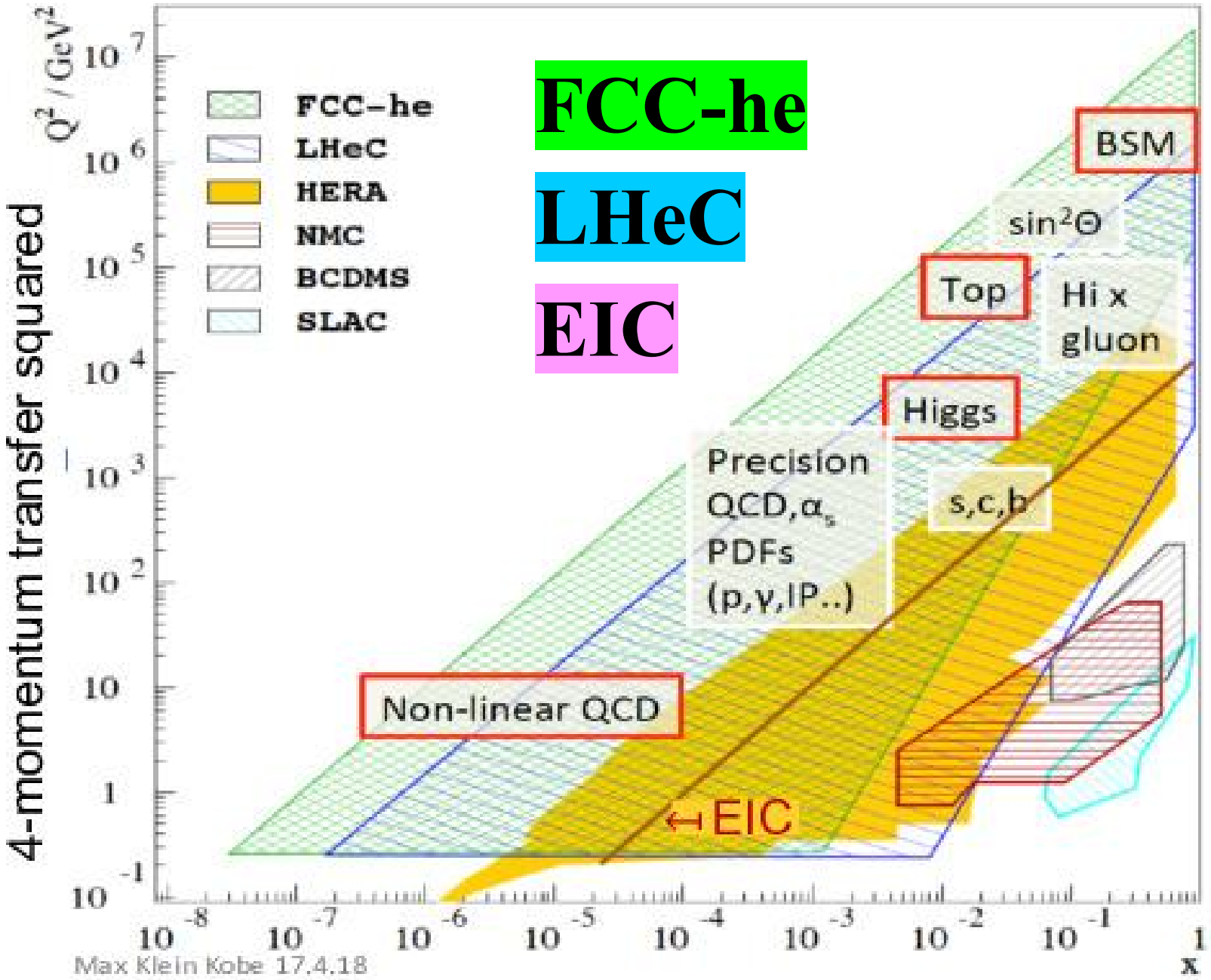






A QCD analysis for nuclear PDFs at NNLO
M. Walt, I. Helenius, W. Vogelsang
ArXiv:1908.04983

Future Facilities

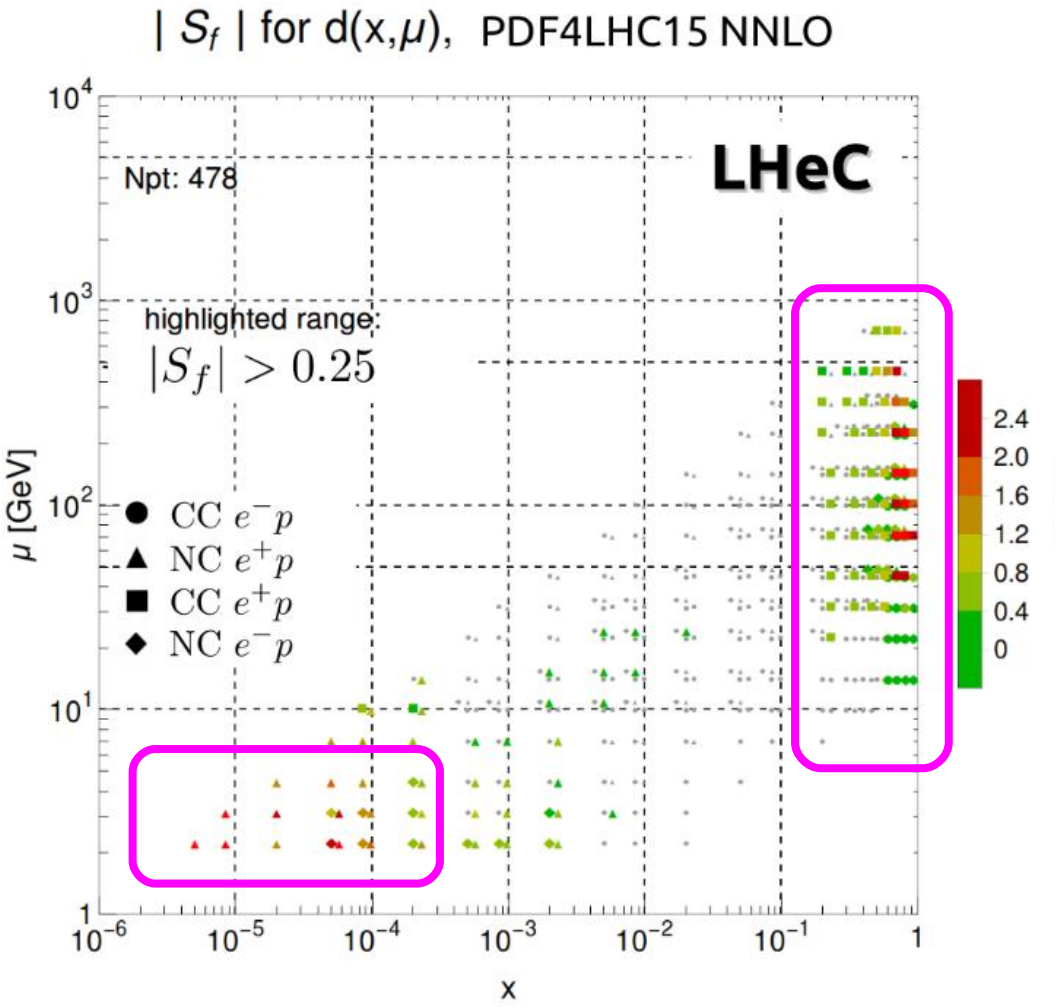

4-momentum transfer squared
Q² / GeV²
FCC-he
LHeC
HERA
NMC
BCDMS
SLAC
FCC-he
LHeC
EIC
BSM
sin²Θ
Top
Hi x gluon
Higgs
Precision QCD,α_s PDFs (p,γ,IP..)
s,c,b
Non-linear QCD
↔EIC
Max Klein Kobe 17.4.18
x

Complementary: LHeC and EIC

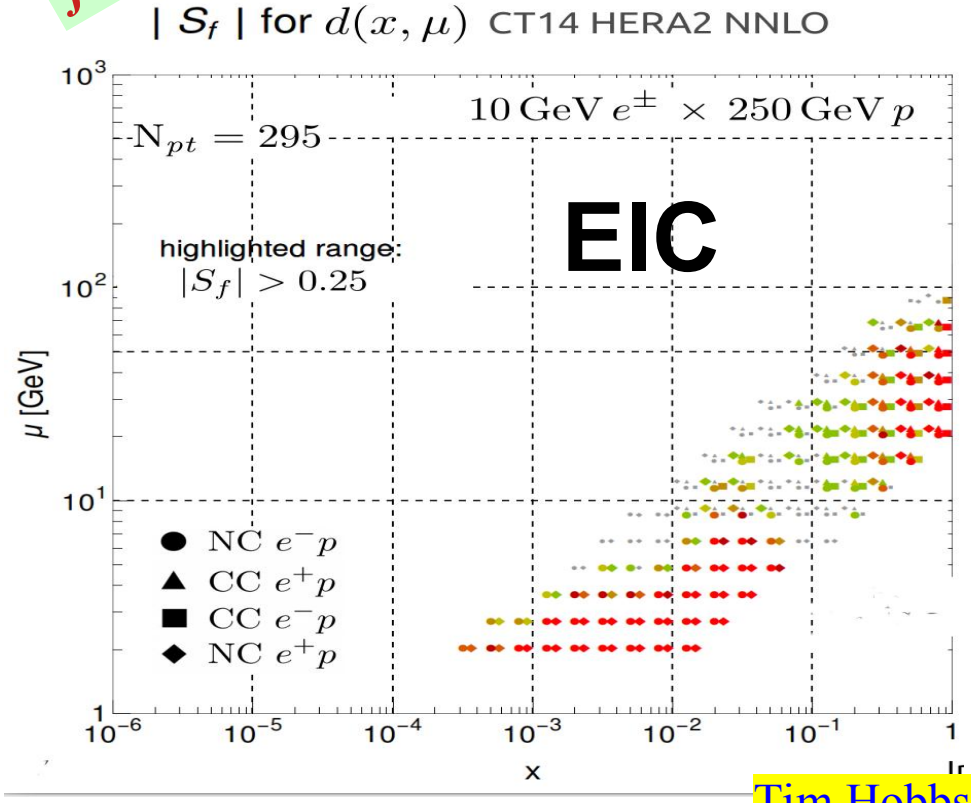
Sensitivity S^F:

Correlation times the scaled residual:

$$S_F \sim C_f \frac{\delta r}{\langle r \rangle_{exp}} \qquad \delta r \sim \frac{T - D}{\sigma}$$



just one flavor



Tim Hobbs

Different Kinematic Regions
Cross-Checks are **Crucial**!!!

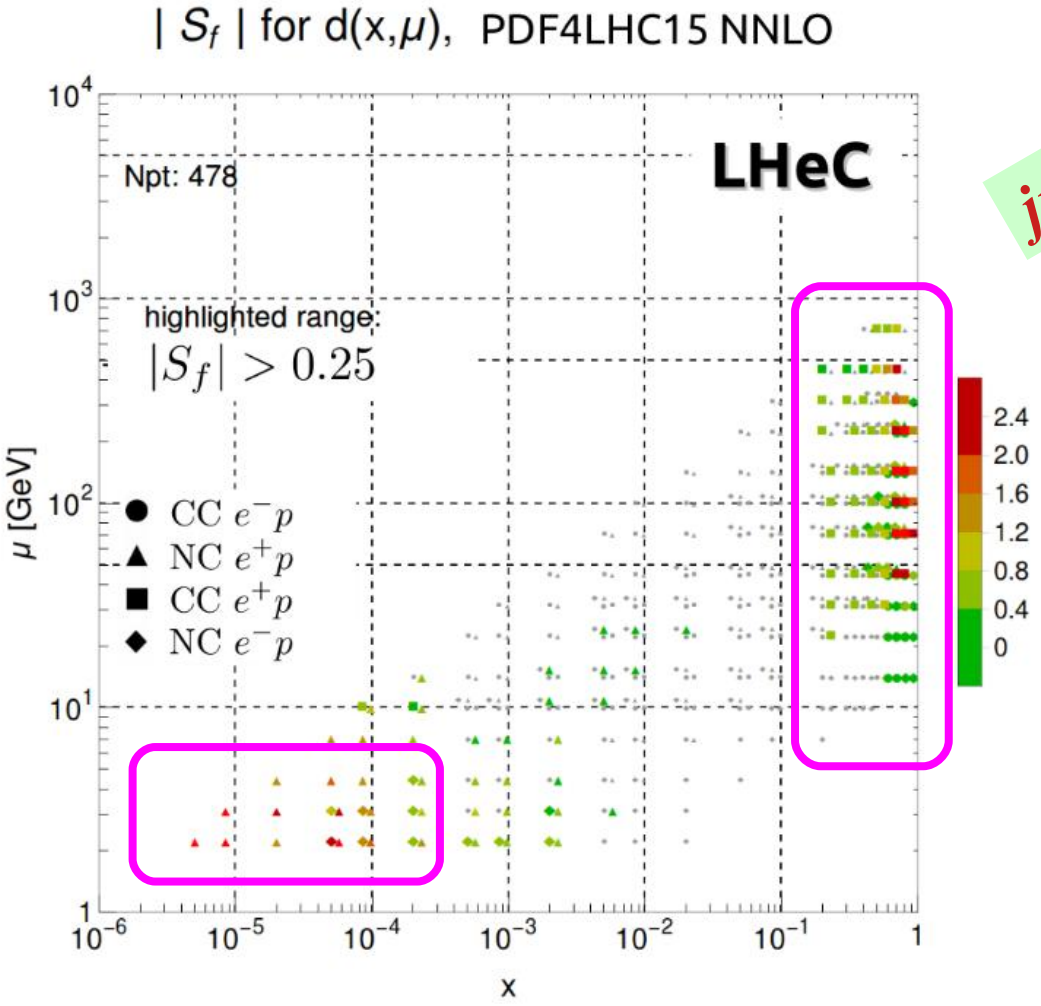
PDFSense: B.-T. Wang, et al., Phys.Rev. D98 (2018) no.9, 094030

Complementary: LHeC and HL-LHC

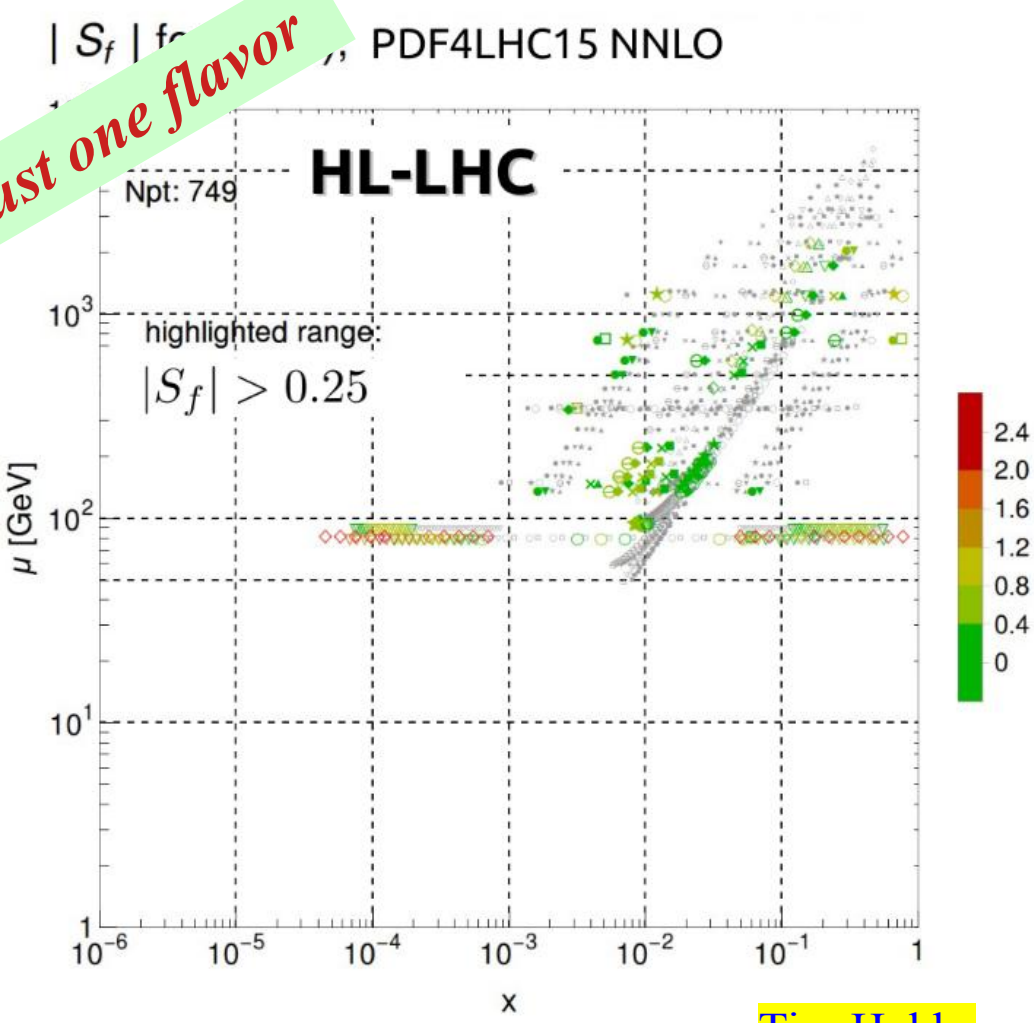
Sensitivity S^F:

Correlation times the scaled residual:

$$S_F \sim C_f \frac{\delta r}{\langle r \rangle_{exp}} \qquad \delta r \sim \frac{T - D}{\sigma}$$



just one flavor



Different Kinematic Regions
Cross-Checks are **Crucial**!!!

Tim Hobbs

PDFSense: B.-T. Wang, et al., Phys.Rev. D98 (2018) no.9, 094030

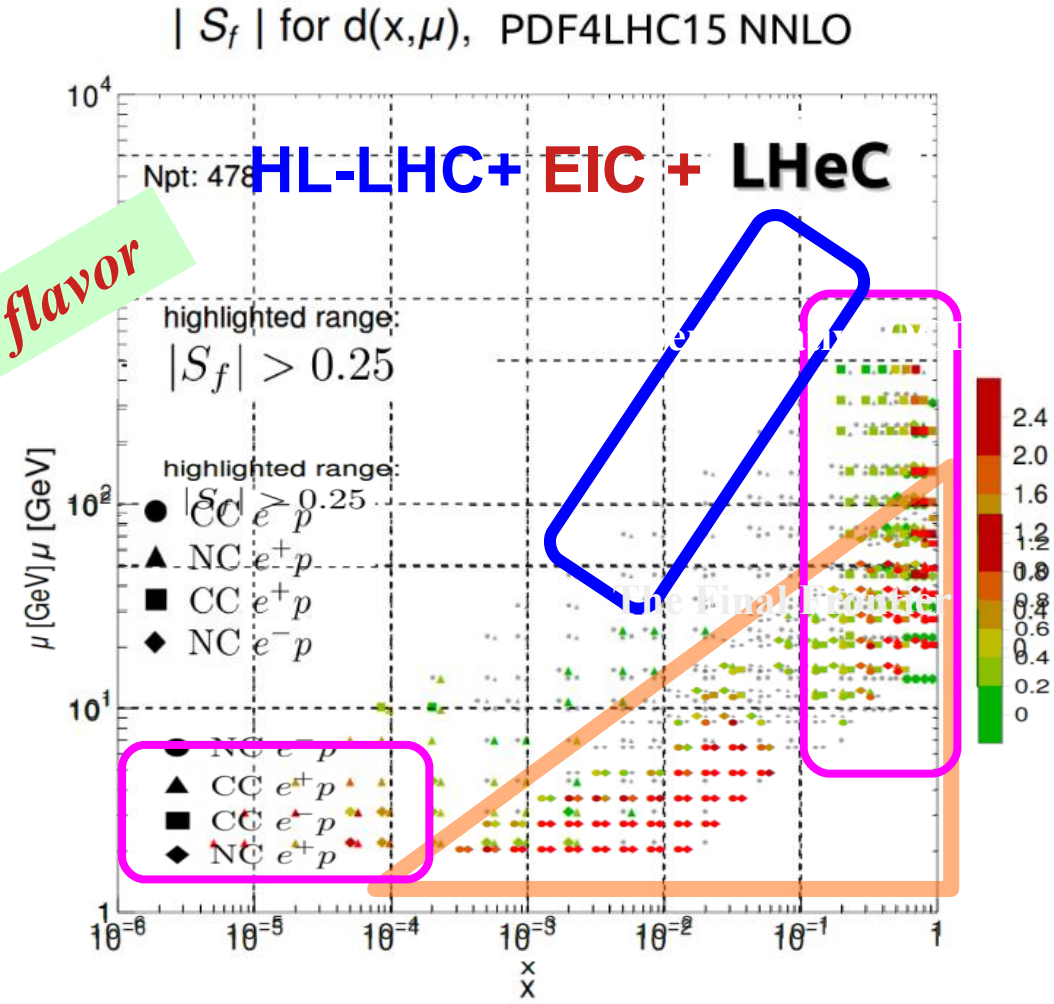
Complementary: LHeC + EIC + HL-LHC

Sensitivity S^F:

Correlation times the scaled residual:

$$S_F \sim C_f \frac{\delta r}{\langle r \rangle_{exp}} \qquad \delta r \sim \frac{T - D}{\sigma}$$

EIC + LHeC + HL-LHC
Maximal coverage



PDFSense: B.-T. Wang, et al.,
Phys.Rev. D98 (2018) no.9, 094030

PDF Update

What are the challenges & opportunities

It will have high statistics for a wide variety of NUCLEI

Nuclear corrections are inextricably linked
to the PDF flavor differentiation

It allows us to push to HI-X

W cuts eliminate much of this region
Higher-twist, factorization violations, …
Test models in $x \rightarrow 1$ limit, e.g., d/u, …

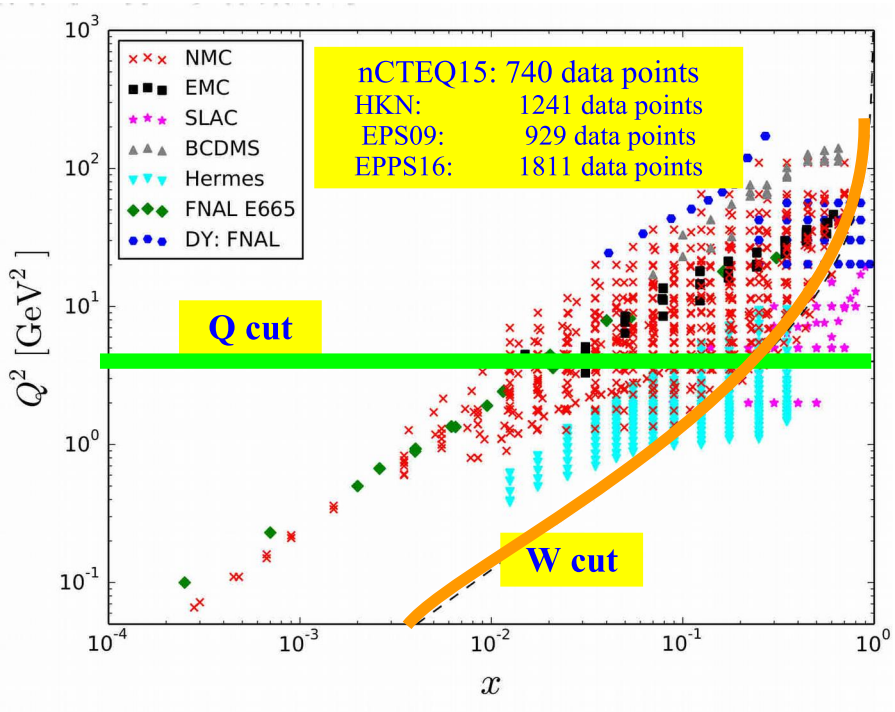
It allows us to push to low Q

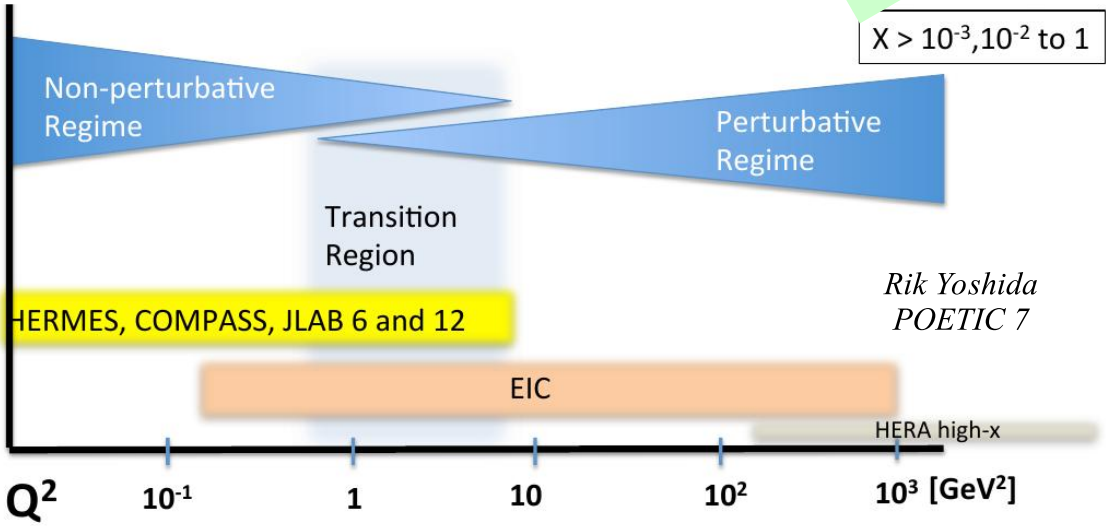
Q cuts eliminate much of this region
Explores the parton/hadron transition
Study non-perturbative collective phenomena

Hadron / Parton Transition:

Higher Twist, many body problem, duality, hi-x, mass corrections ...

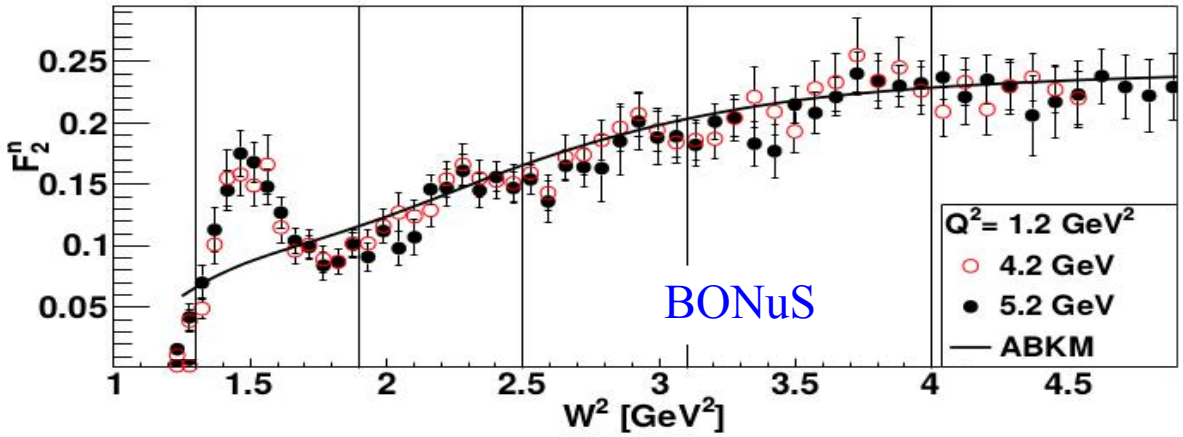
CJ15 Tools & Techniques





Rik Yoshida
POETIC 7

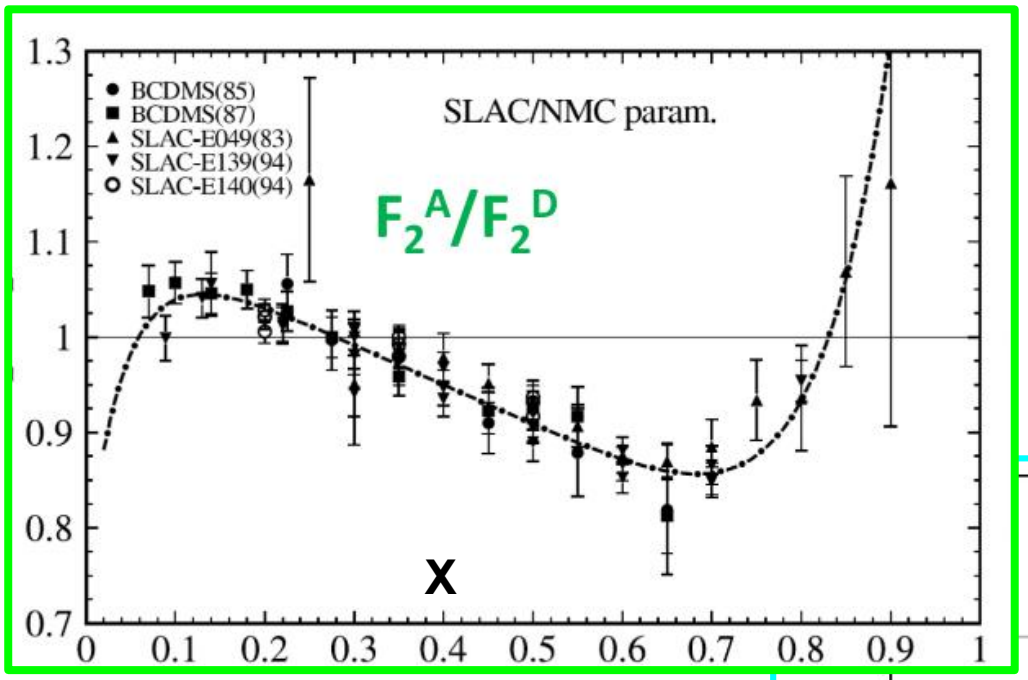
… heard at POETIC



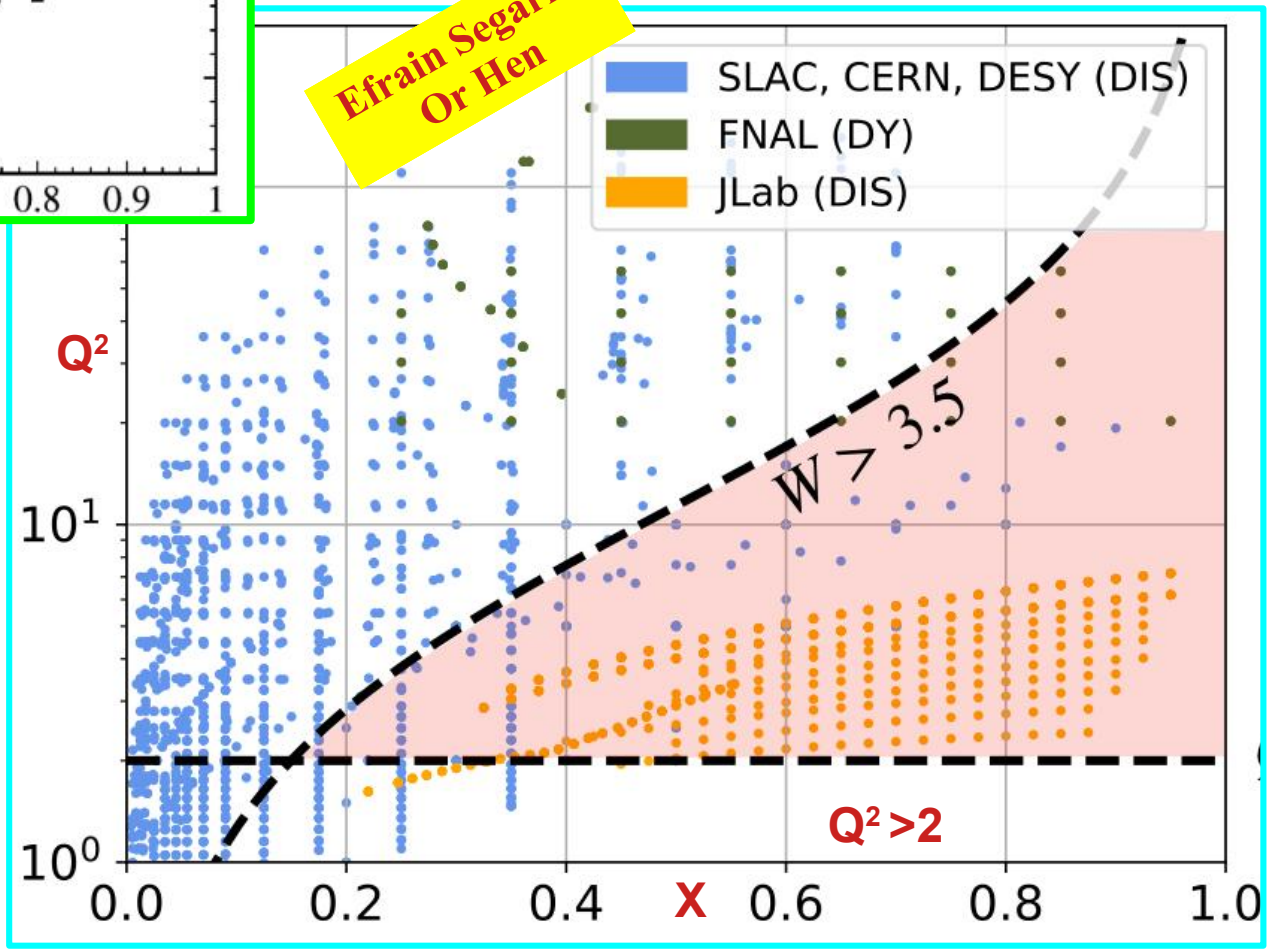
EIC can push these boundaries

… in particular, the quark/gluon to hadron transition

Start with JLab Data: Challenges at Large x & Low Q^2



Nuclear PDFs: x>1 allowed;
impacts F_2^{Nuc}/F_2^{Iso} in Fermi region
Higher Twist
Isospin violation: u⇔d
d/u limits as x→1



JLab Data @ Hi-X Low-Q^2

Current nCTEQ framework
must be extended
to accommodate this region

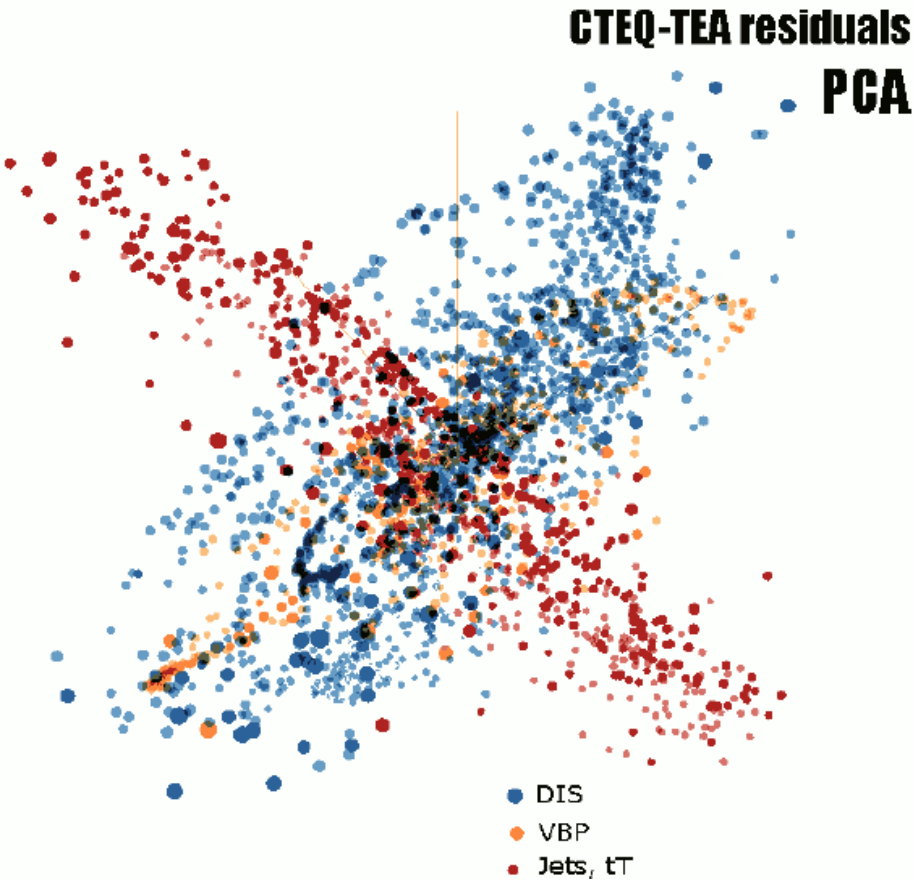
lots of work to do ...

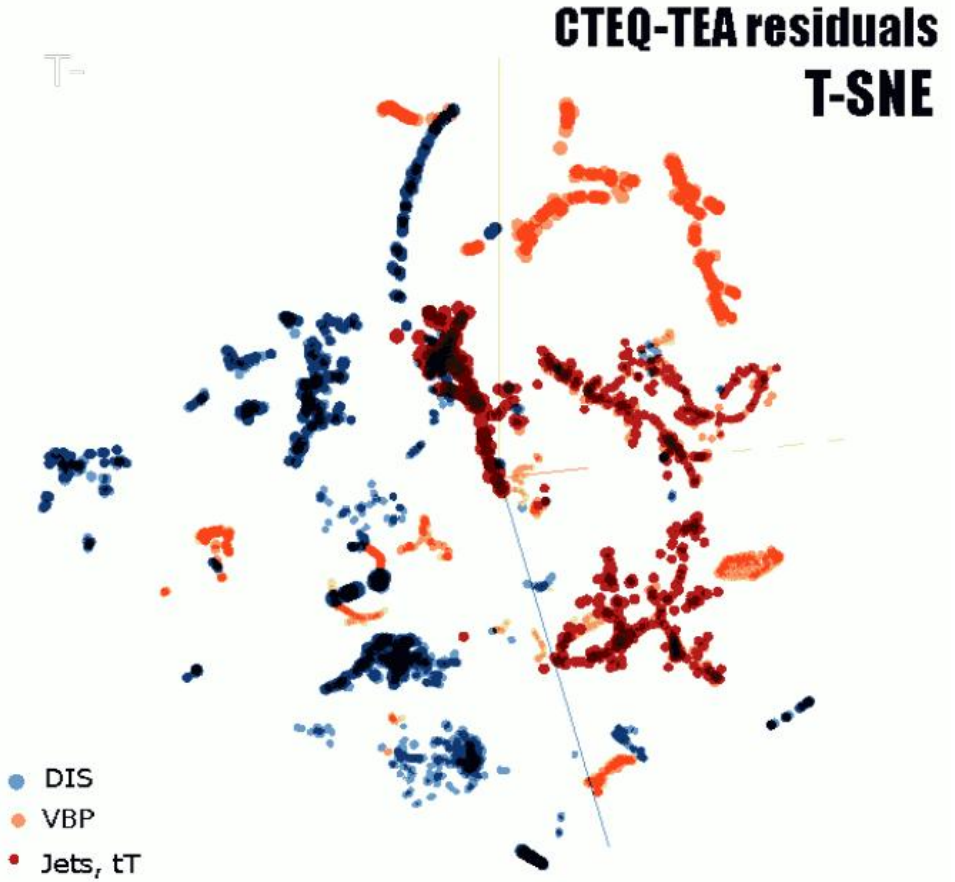
INNOVATIVE IDEAS

borrow from AI

Artificial Intelligence Tools: Projector tool of Google TensorFlow

Reads two .tsv files with vectors and metadata (descriptions of data points)





Principal Component Analysis (PCA) visualizes the 56-dim. manifold by reducing it to 10 dimensions (à la META PDFs)

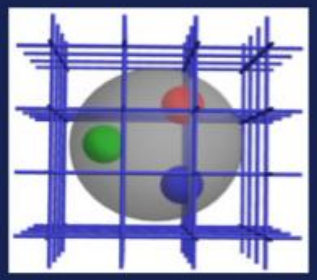
PDFSense tool

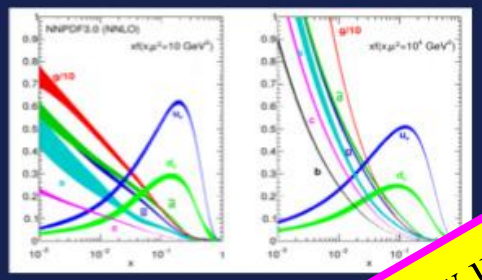
t-distributed stochastic neighbor embedding (**t-SNE**) sorts vectors according to their similarity

https://metapdf.hepforge.org/PDFSense/

http://projector.tensorflow.org

Dynamical projections for the visualization of PDFSense data
Dianne Cook, Ursula Laa, German Valencia arXiv:1806.09742





Parton Distributions and Lattice Calculations in the LHC era
(PDFLattice 2017)

22-24 March 2017, Oxford, UK

Follow up last month

Review

Progress in Particle and Nuclear Physics 100 (2018) 107–160

Parton distributions and lattice QCD calculations: A community white paper

Huey-Wen Lin [1,2], Emanuele R. Nocera [3,4], Fred Olness [5], Kostas Orginos [6,7], Juan Rojo [8,9,*] (editors), Alberto Accardi [7,10], Constantia Alexandrou [11,12], Alessandro Bacchetta [13], Giuseppe Bozzi [13], Jiunn-Wei Chen [14], Sara Collins [15], Amanda Cooper-Sarkar [16], Martha Constantinou [17], Luigi Del Debbio [4],

See talk by: Emanuele Nocera

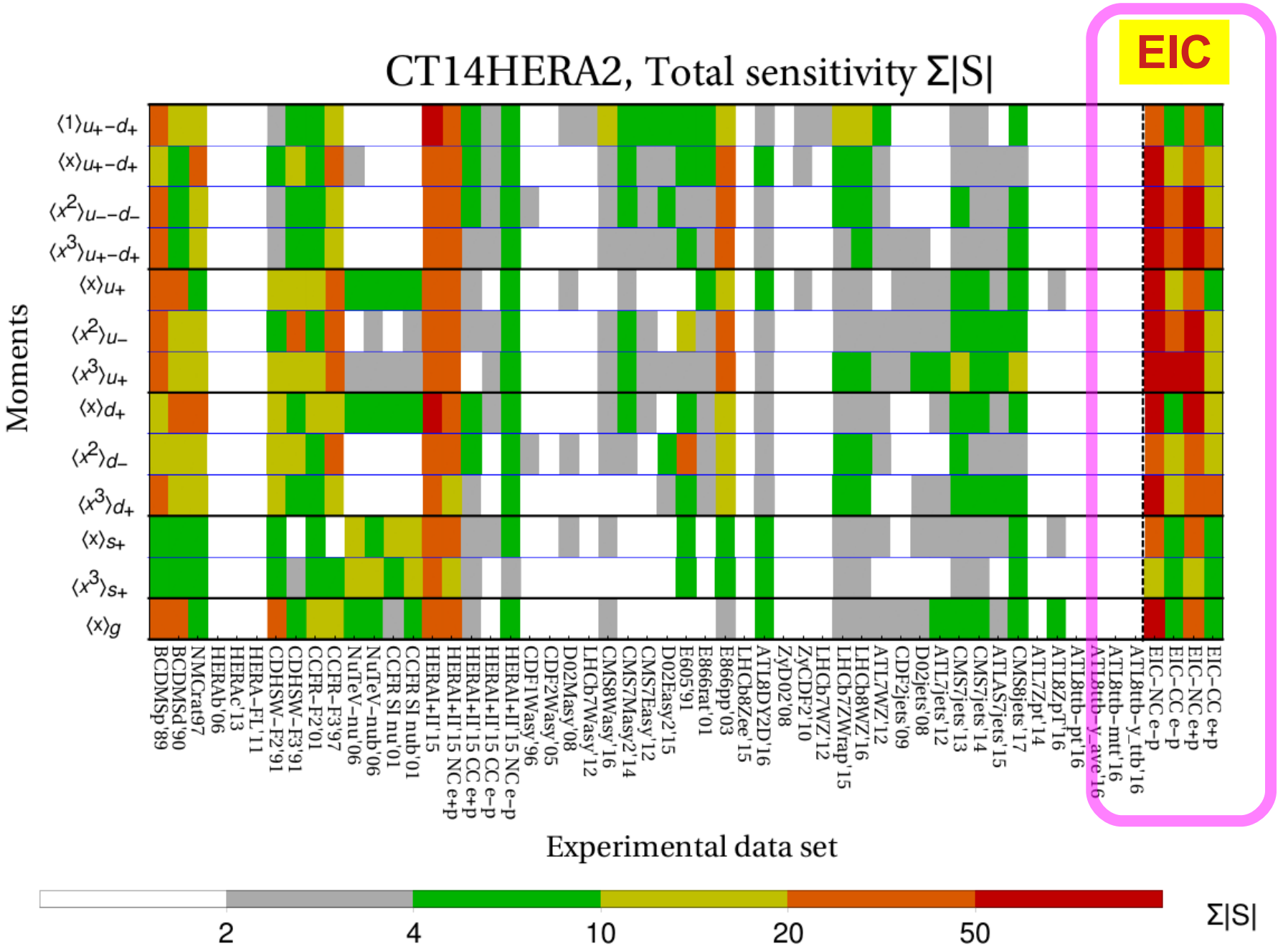
Table B.1
Status of current lattice-QCD calculations of the first moments of unpolarized PDFs. All results are quoted at $\mu^2 = 4$ GeV^2. We use the abbreviations Disc (discretization), QM (quark mass), FV (finite volume), Ren (renormalization) and ES (excited states) to denote the corresponding sources of uncertainty.

Mom.	Collab.	Ref.	N_f	Status	Disc [fm]	QM	FV	Ren	ES	
$\langle x\rangle_{u^+-d^+}$	ETMC 15	[263]	2+1+1	P	0.06, 0.08	–	■, ★	★, ★	■, ★	Fig. B.1(
	ETMC 15	[263]	2	P	0.06–0.09	–	○	★	■	Fig
	RQCD 14	[251]	2	P	0.06–0.08	–	○	★	○	
$\langle x\rangle_{q^+}$	ETMC 13	[276]	2+1+1	P	0.08	–	★	★	★	
	χQCD 13	[277]	0	P	■	■	■	○	■ [b]	= 0.451(37),
	χQCD 13	[277]	0	P	■	■	■	○	■ [bc]	$\langle x\rangle_{d^+}$ = 0.188(20
	χQCD 13	[277]	0	P	■	■	■	○	■ [bc]	$\langle x\rangle_{s^+}$ = 0.0
$\langle x\rangle_g$	ETMC 13	[278]	2+1+1	P	0.08	–	★	○	★	Fig. B
	χQCD 13	[277]	0	P	■	■	■	○	★ [c]	0.
	QCDSF 12	[113]	0	P	■	■	★	★	– [b]	0.43

nPDFs from LQCD Amy Nicholson

Low A useful!!!

EIC Pseudo-Data: Lattice QCD Constraints: PDF Moments

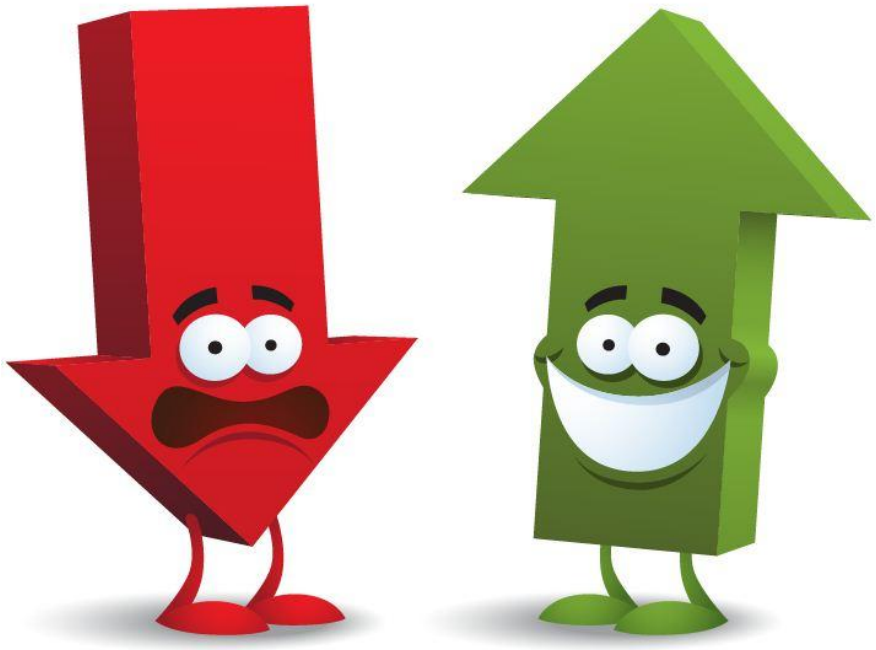


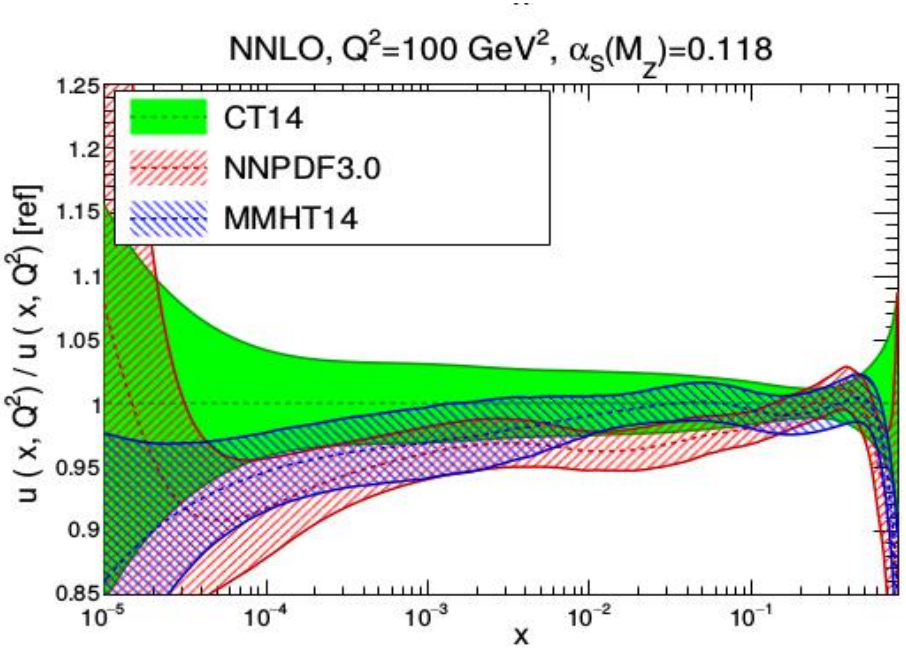
The coming synergy between lattice QCD and high-energy phenomenology
T.J. Hobbs, Bo-Ting Wang, Pavel M. Nadolsky, Fredrick I. Olness: arXiv:1904.00022 [hep-ph]

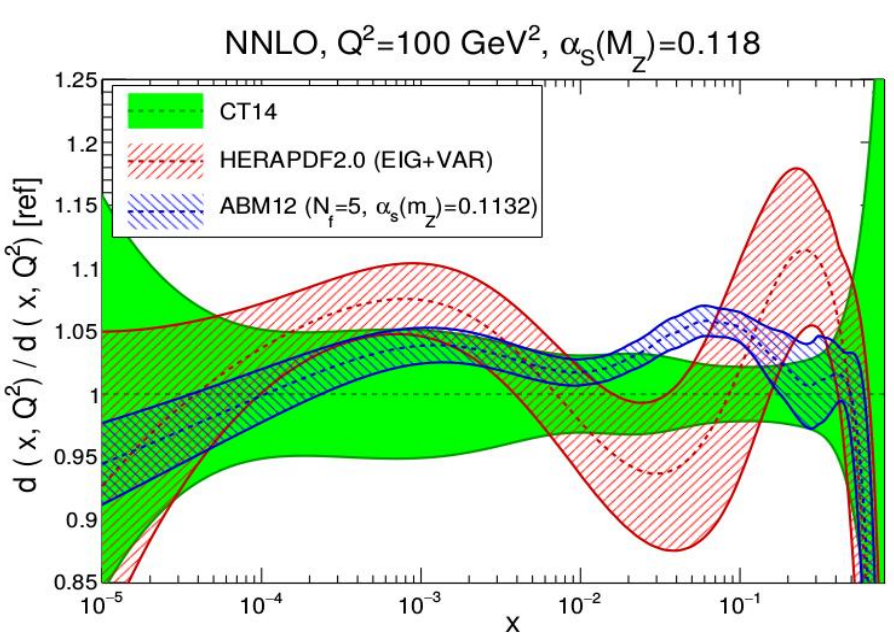
… a brief tour

of the flavors

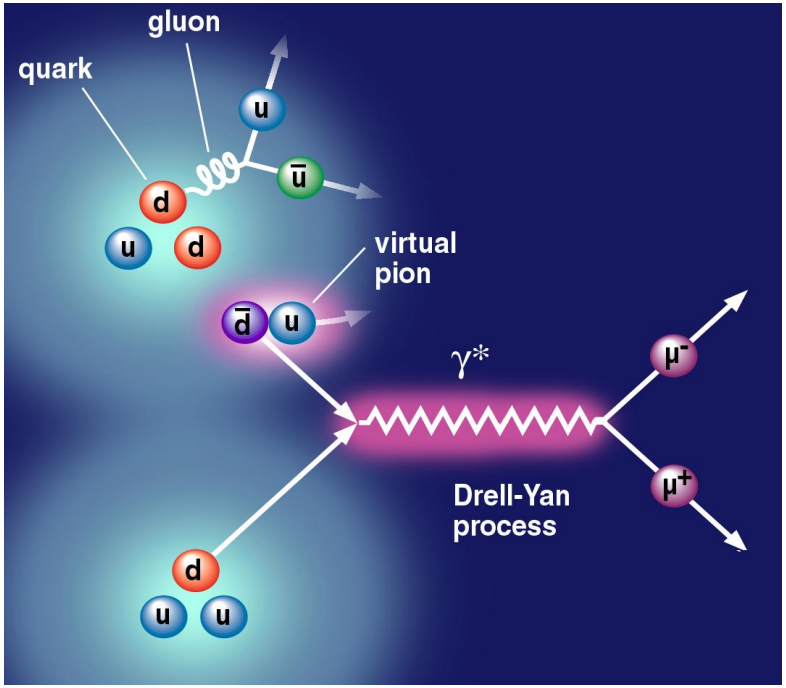
Down & Up




NNLO, Q^2=100 GeV^2, $\alpha_S(M_Z)$=0.118
CT14
NNPDF3.0
MMHT14
u (x, Q^2) / u (x, Q^2) [ref]
x

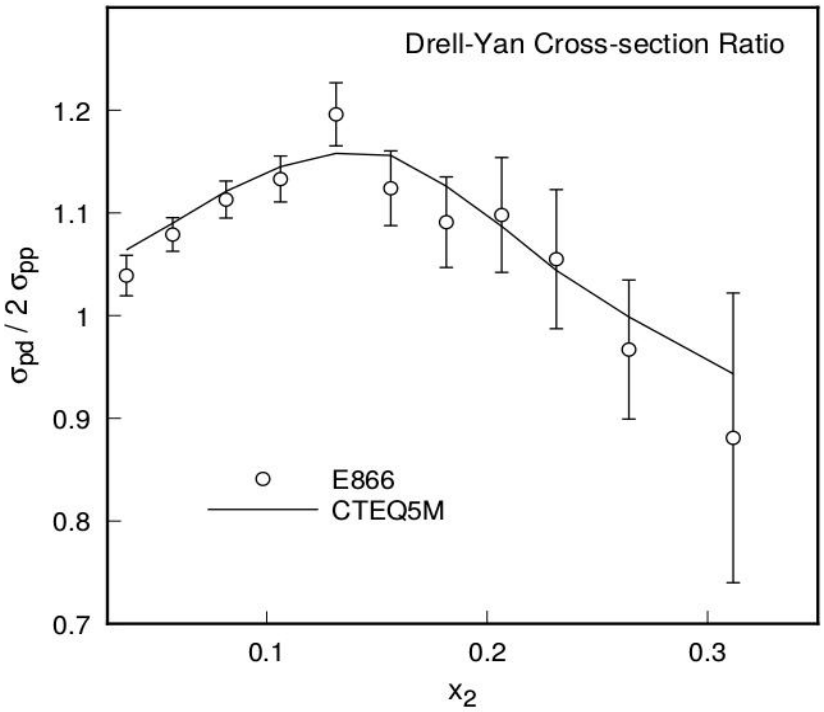

NNLO, Q^2=100 GeV^2, $\alpha_S(M_Z)$=0.118
CT14
HERAPDF2.0 (EIG+VAR)
ABM12 (N_f=5, $\alpha_s(m_Z)$=0.1132)
d (x, Q^2) / d (x, Q^2) [ref]
x

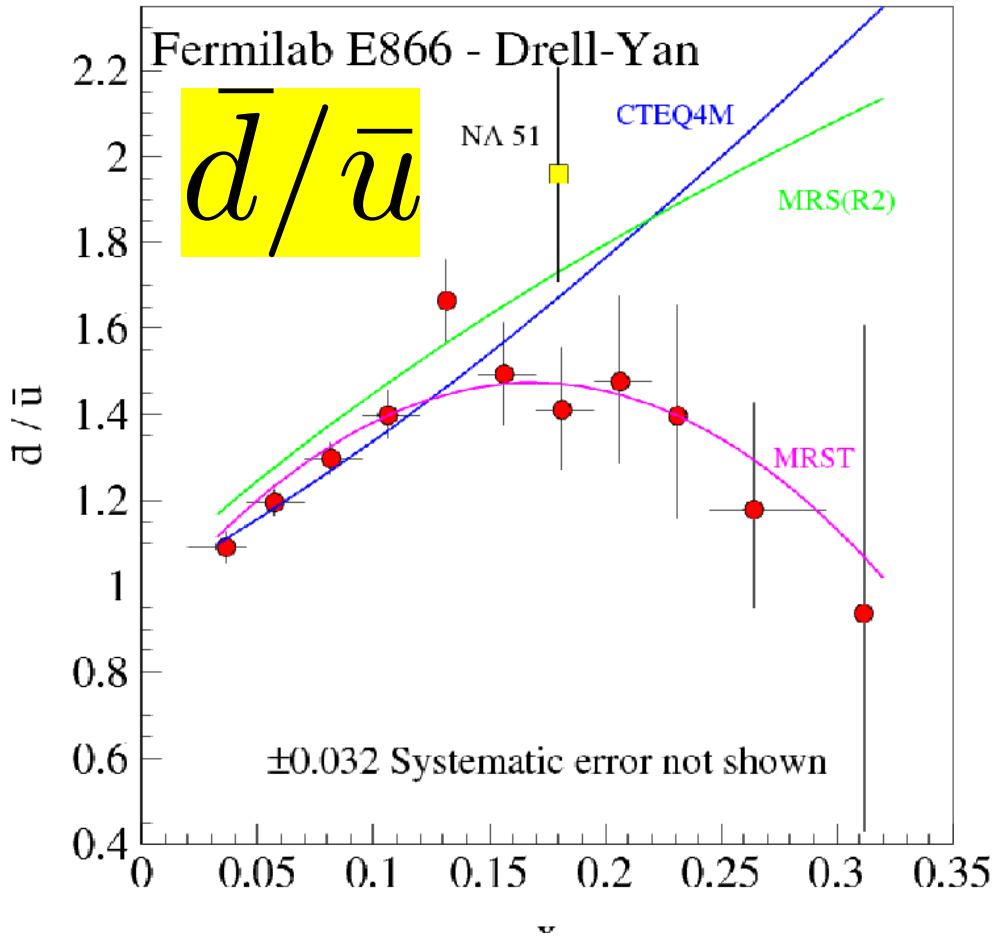
d-bar/u-bar Ratio: A Longstanding Puzzle



Fermilab E866/NuSea
E906 SeaQuest

$$800\ \text{GeV}\ p + p \text{ and } p + d \rightarrow \mu^+\mu^- X$$

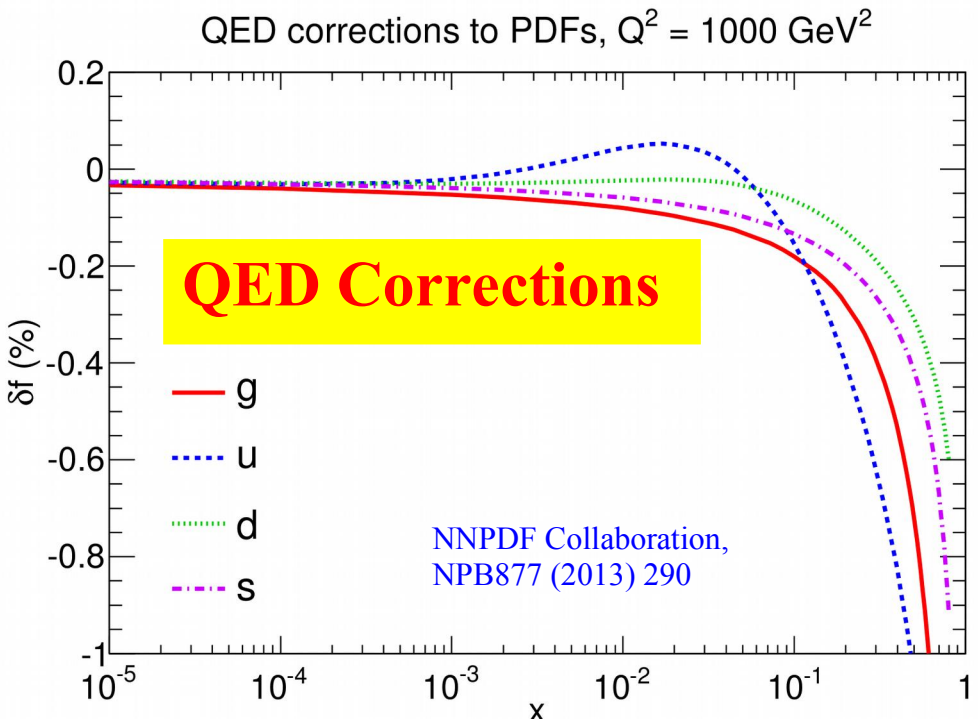




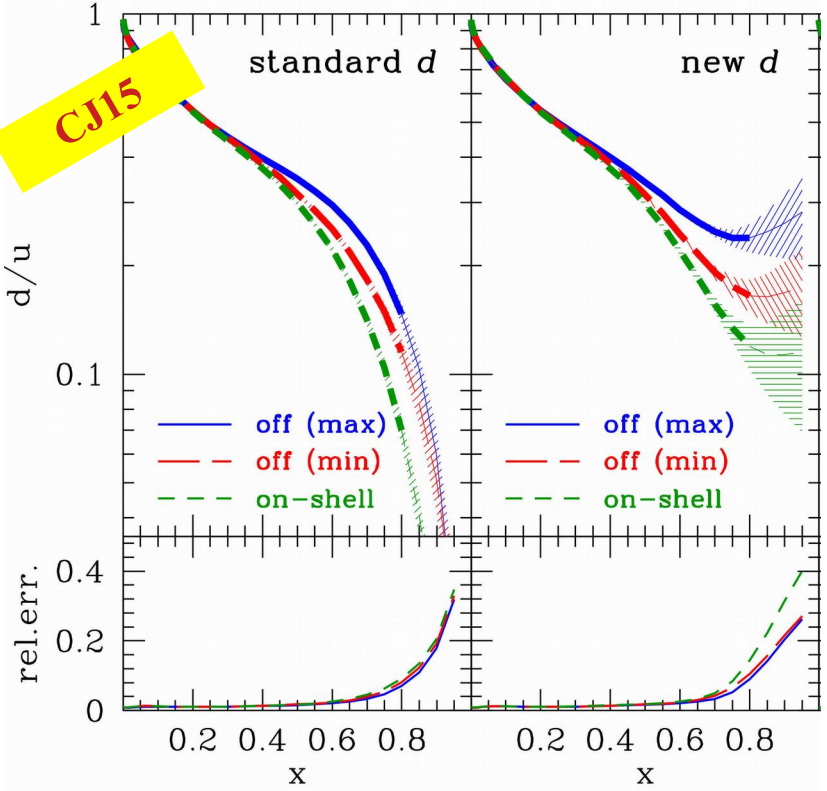
More interesting things,

particularly at large-x

Hi-x Issues: Isospin Symmetry Violation, Higher Twist, x→1 ...

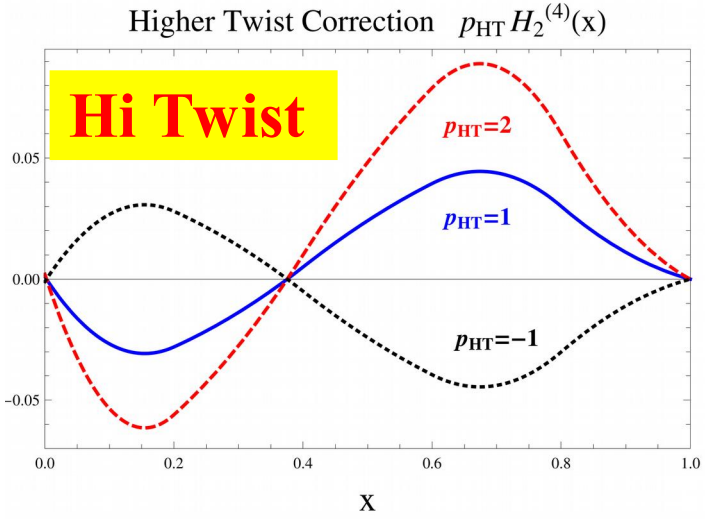


QED Corrections

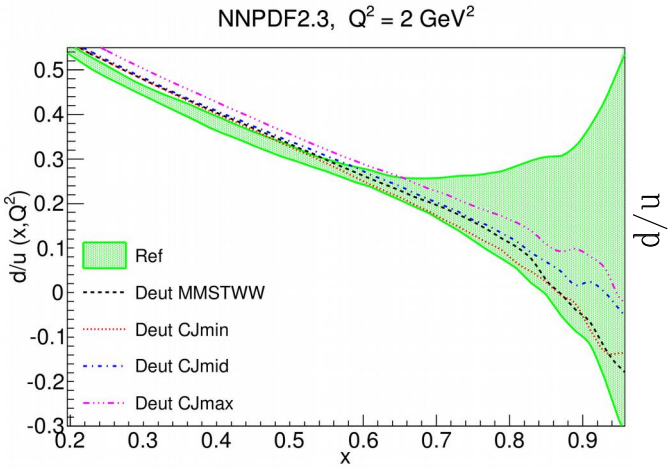


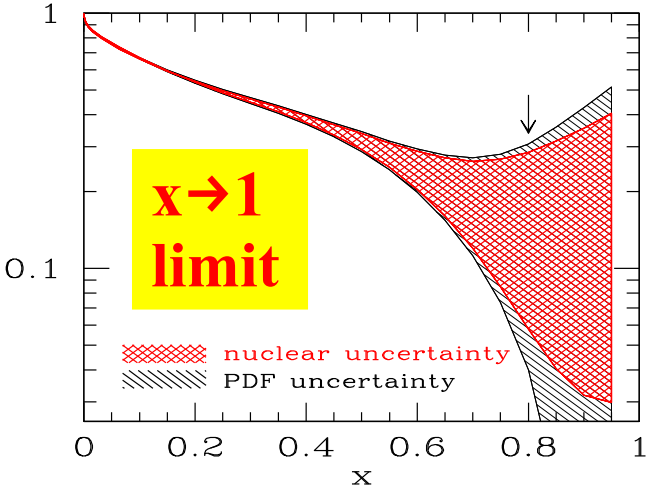
Hi-x is a "Gold Mine" for EIC

Clever Parameterization at large x



Hi Twist

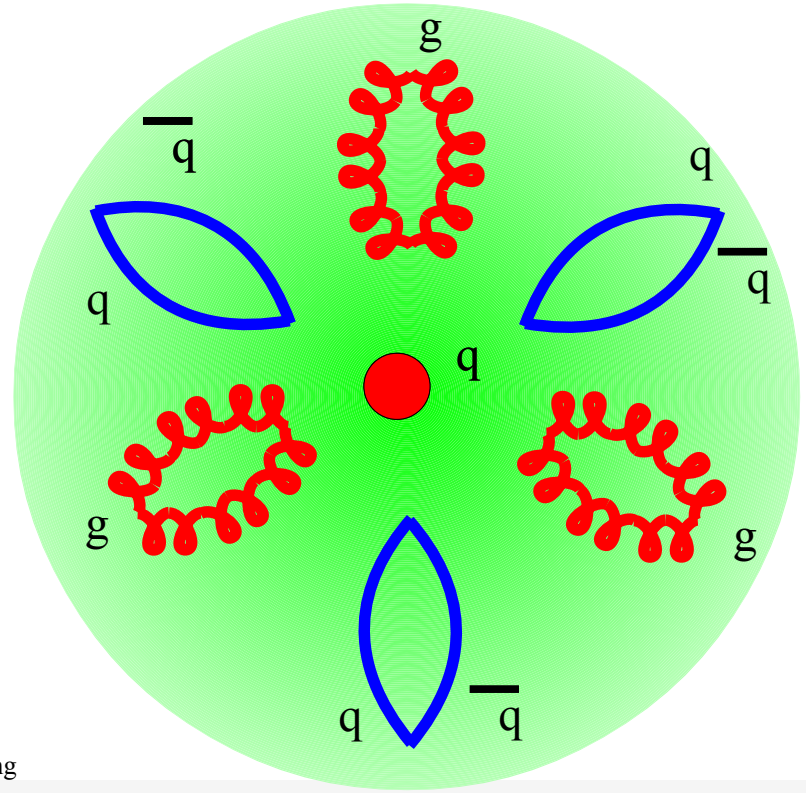




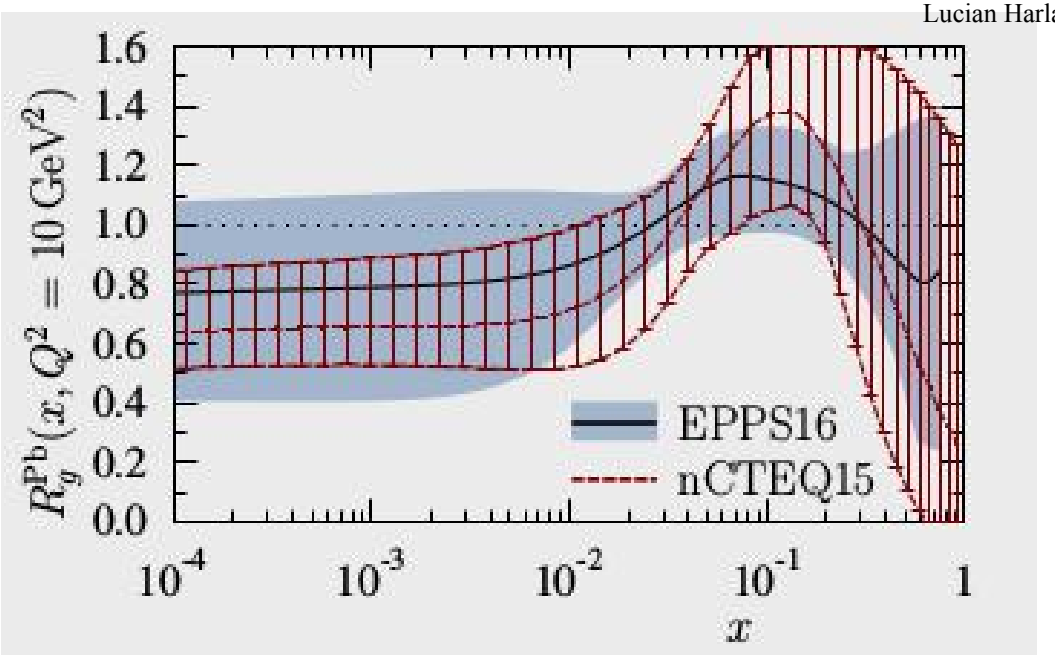
The NNPDF Collaboration, PLB723 (2013) 330

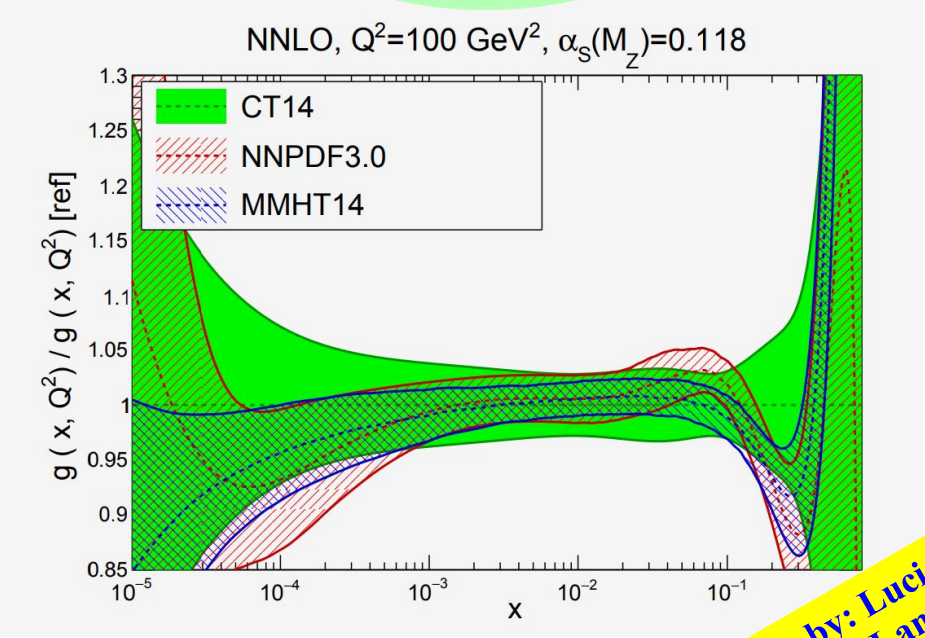
CTEQ-CJ: Phys.Rev. D84 (2011) 014008

GLUON



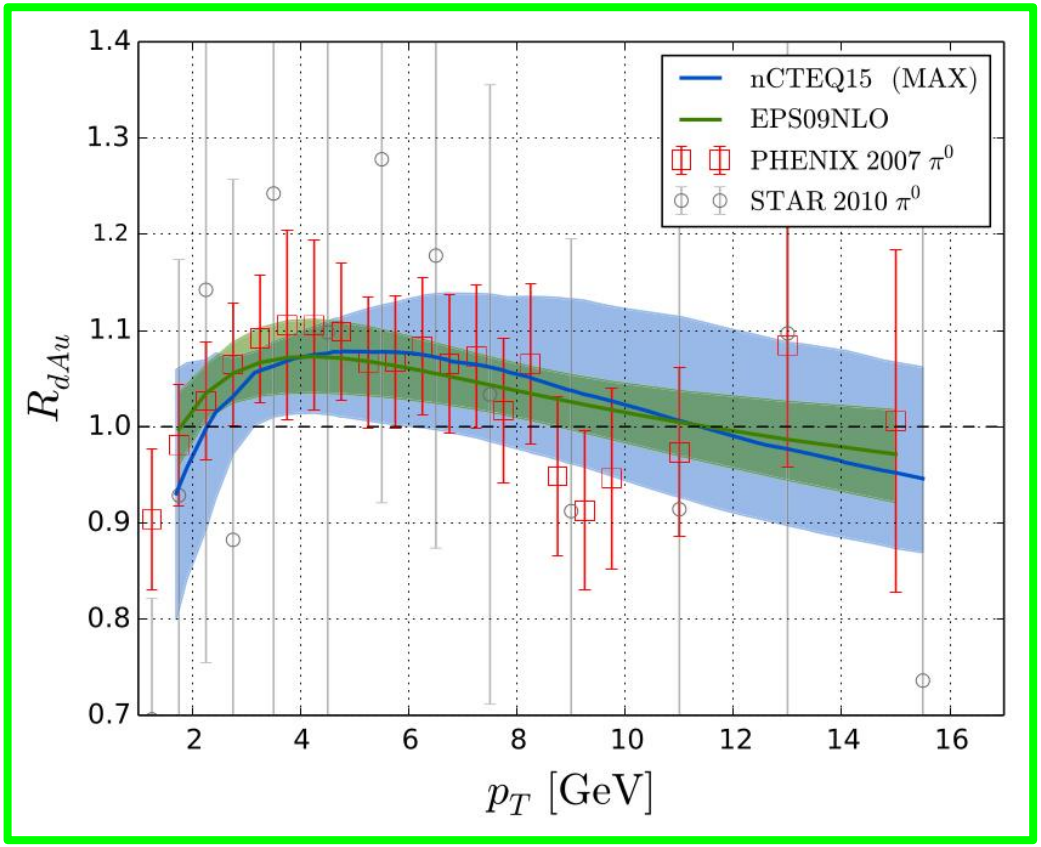
Lucian Harland-Lang

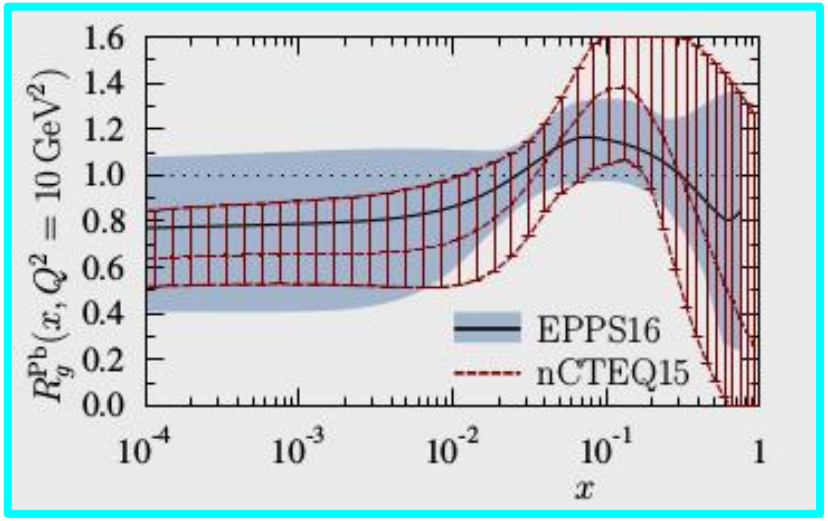


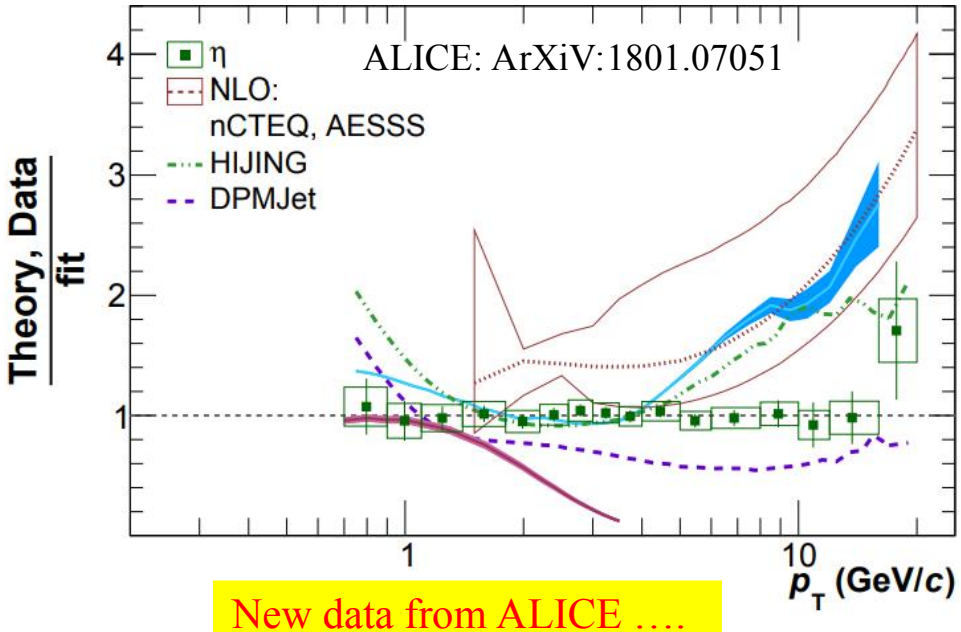


See talk by: Lucian Harland-Lang

PHENIX & STAR:
Pion Production in p+p and d+Au



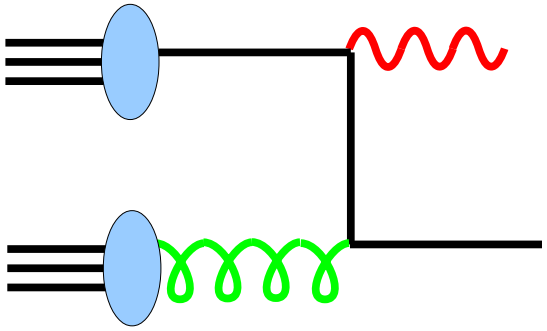




New data from ALICE ….

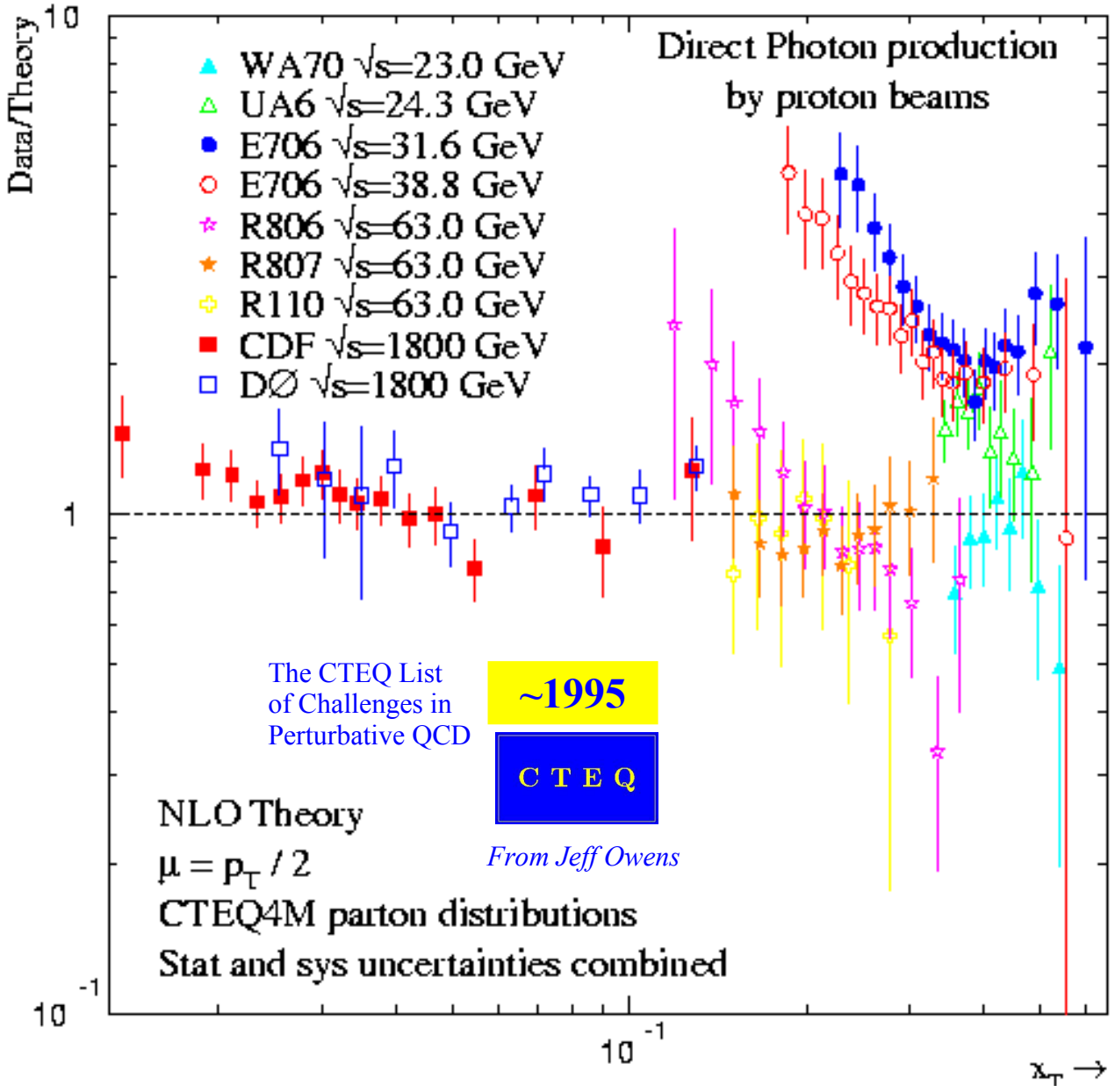
depends on fragmentation function

Nuclear Gluon: Could we use Direct Photon???

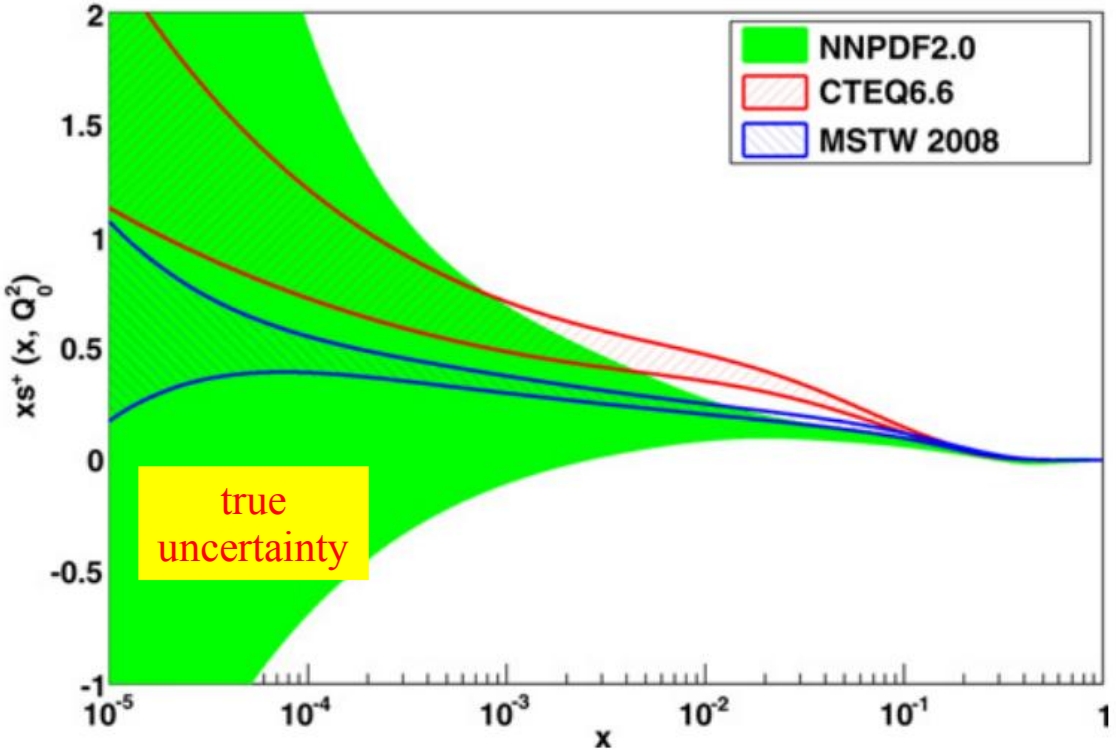


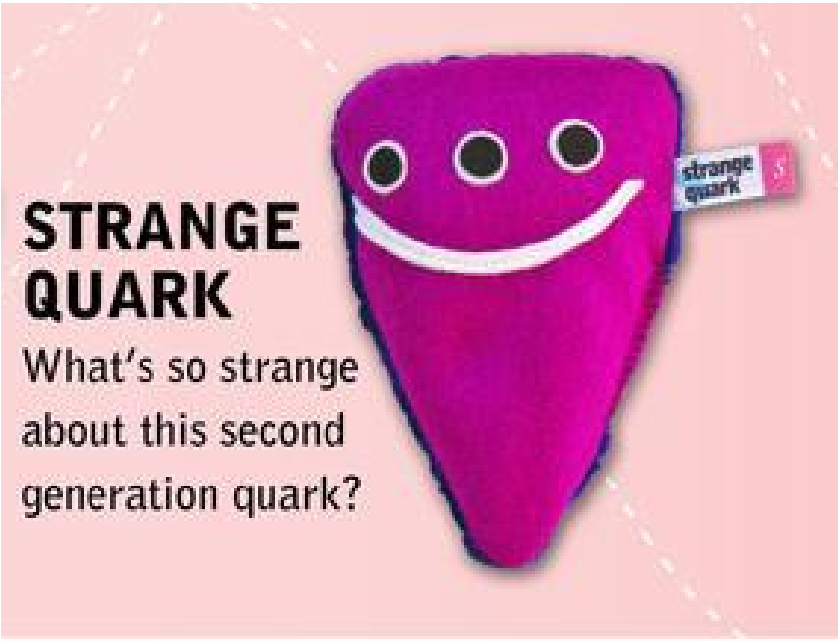
Historically Challenging Intrinsic K_T Issues

Recent improvements in resummation techniques

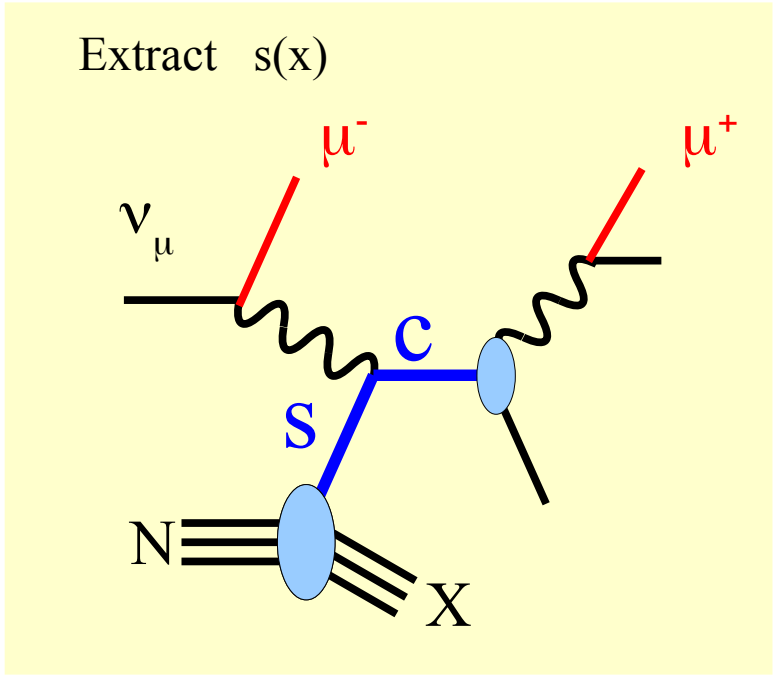


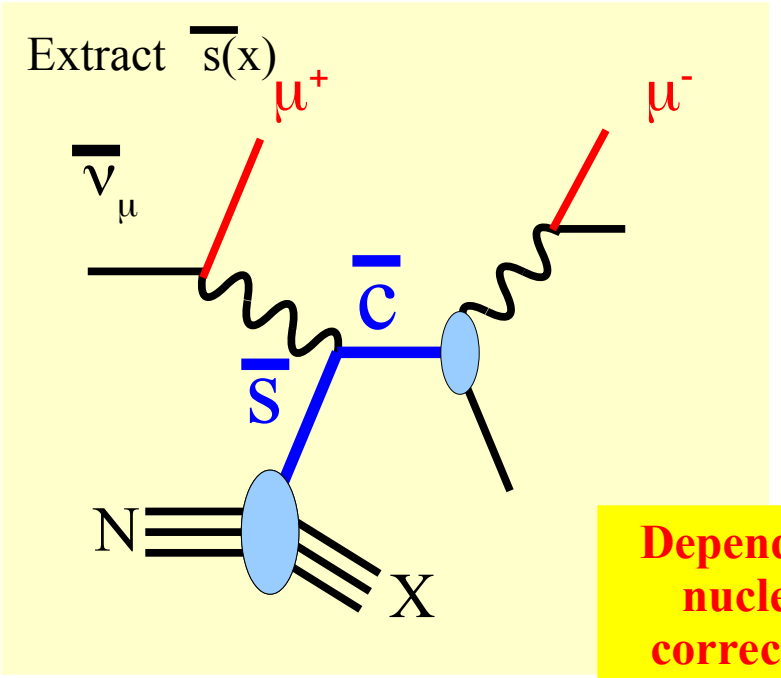
Progress on strange PDF





Di-muon production ⇒ Extract s(x) Parton Distribution

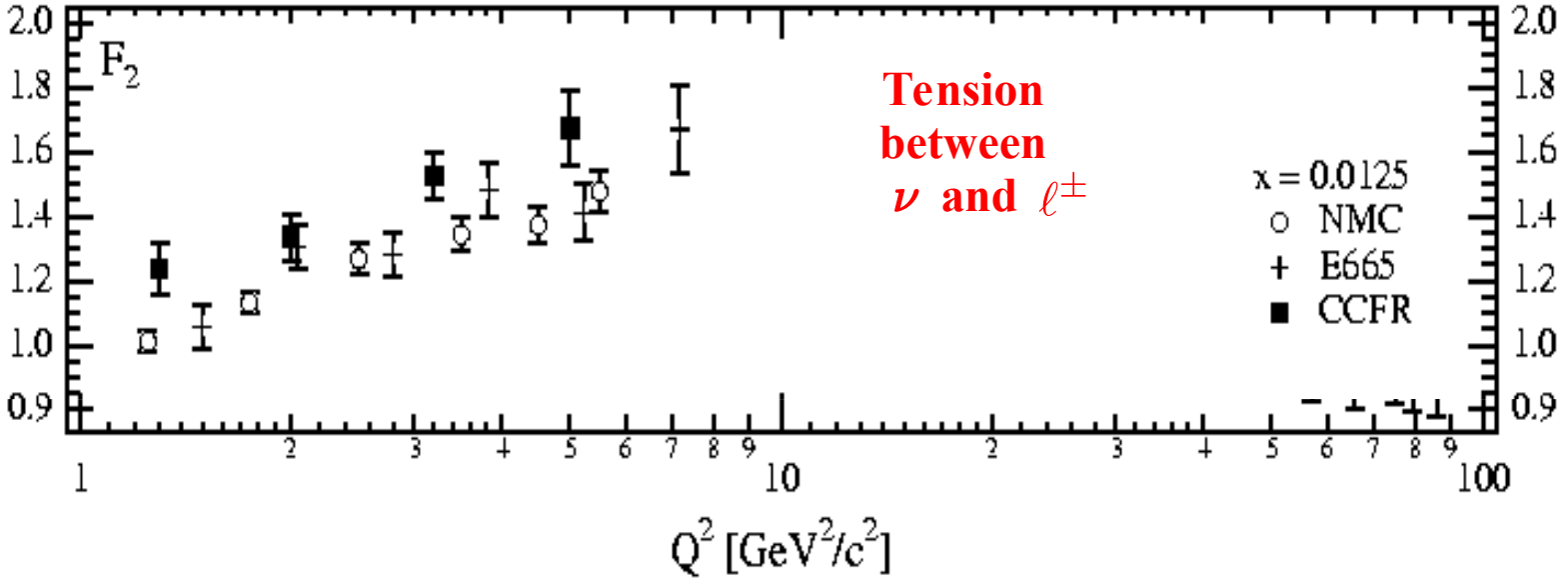




Depends on nuclear corrections

Can extract s(x) and $\bar{s}(x)$ separately

Used in CTEQ Fits

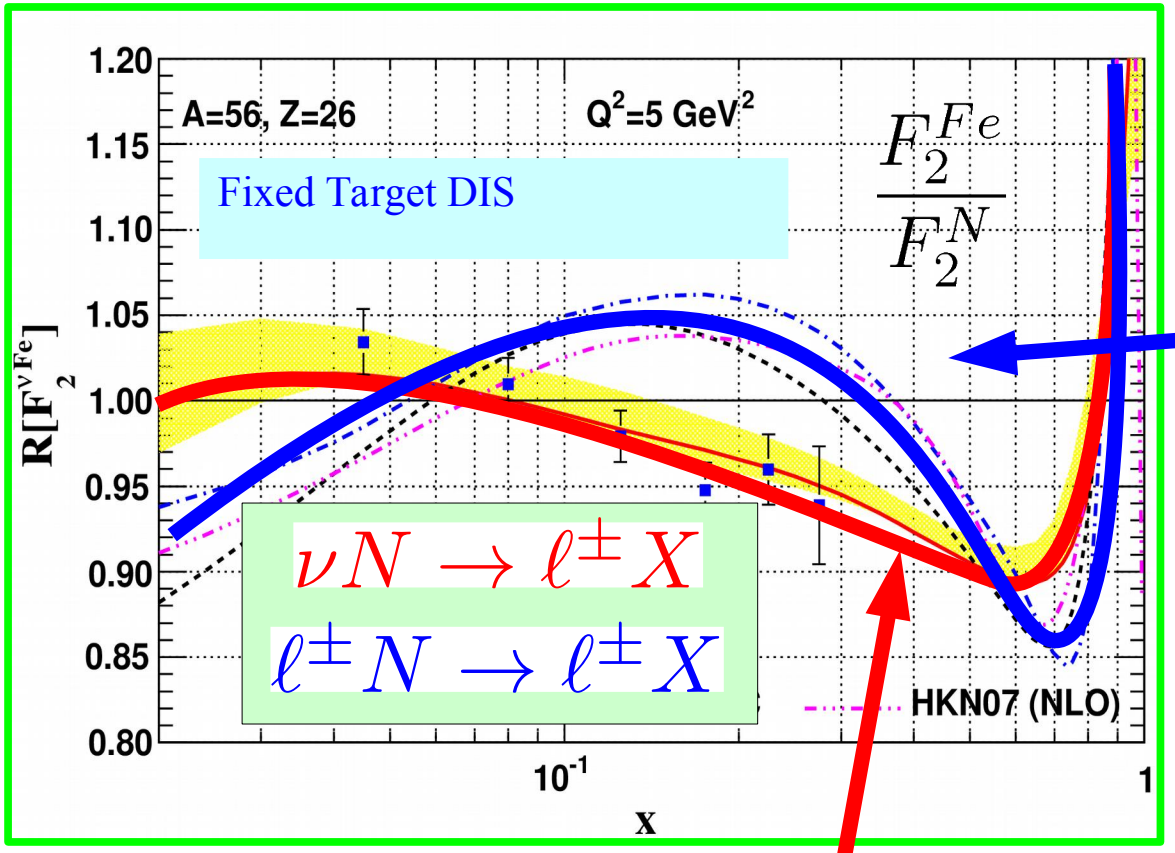


The CTEQ List of Challenges in Perturbative QCD

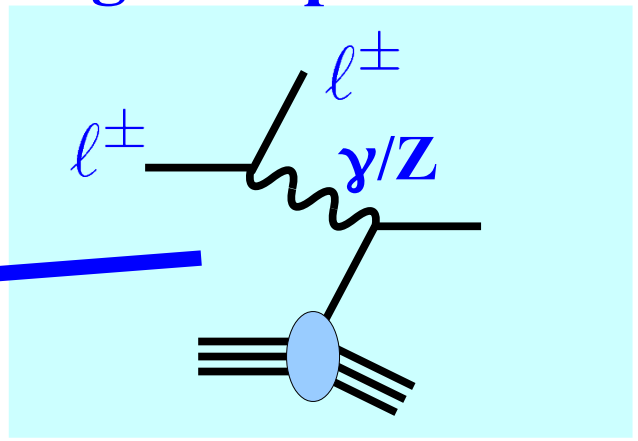
~1995

From Jeff Owens

C T E Q



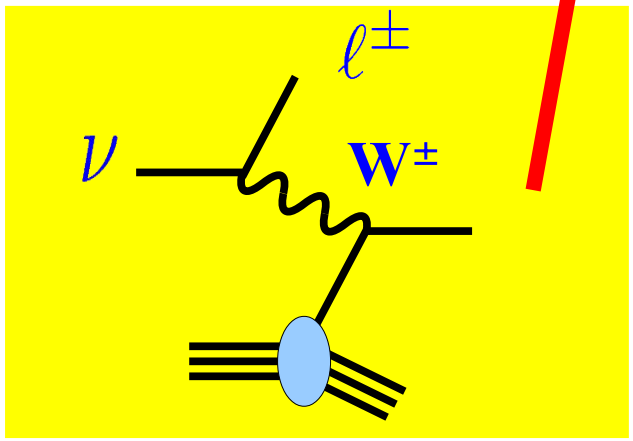
Charged Lepton DIS



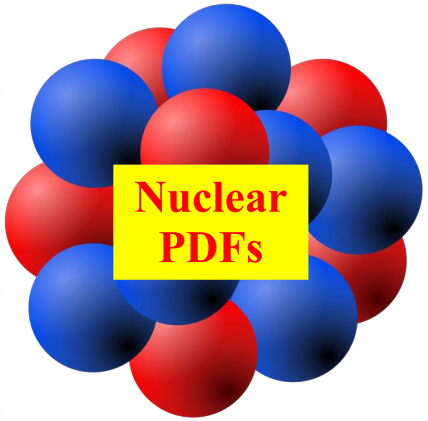
Recurring Theme

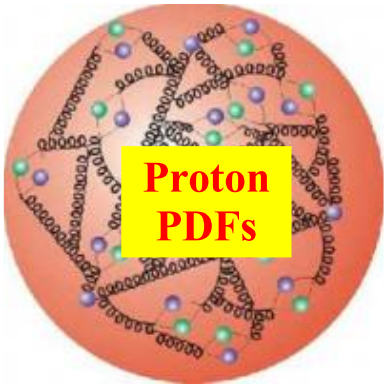
some caveats
... correlated errors

Depends on nuclear corrections

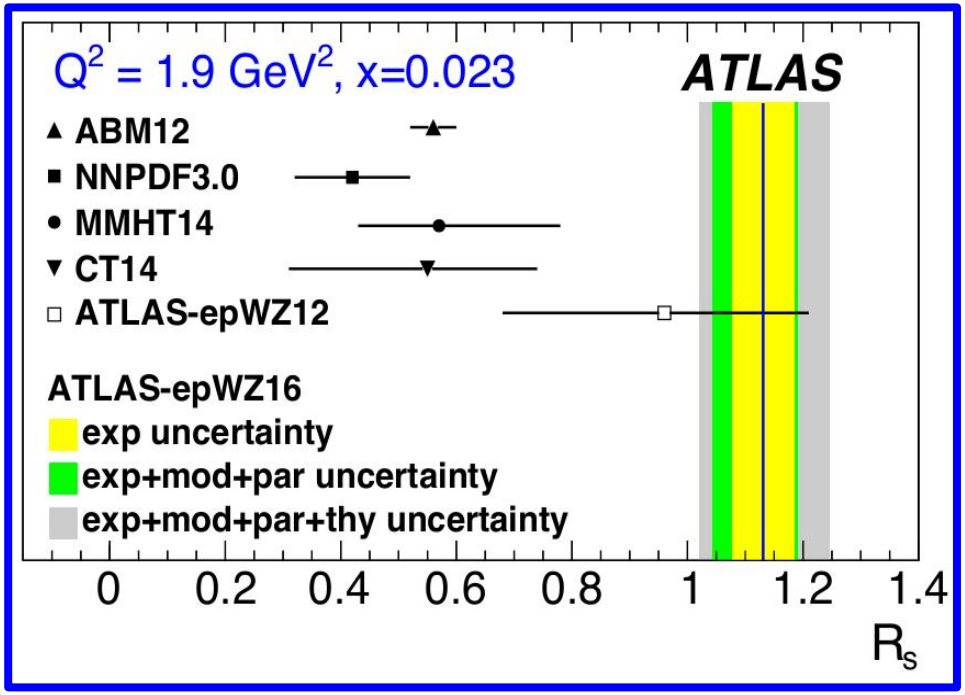


Neutrino DIS

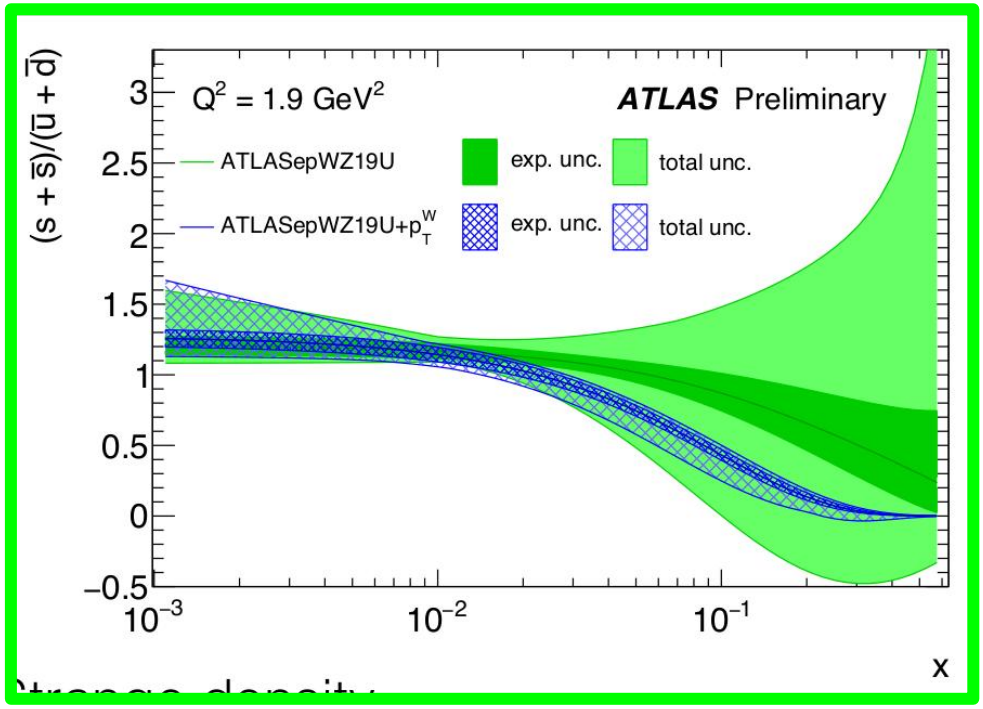


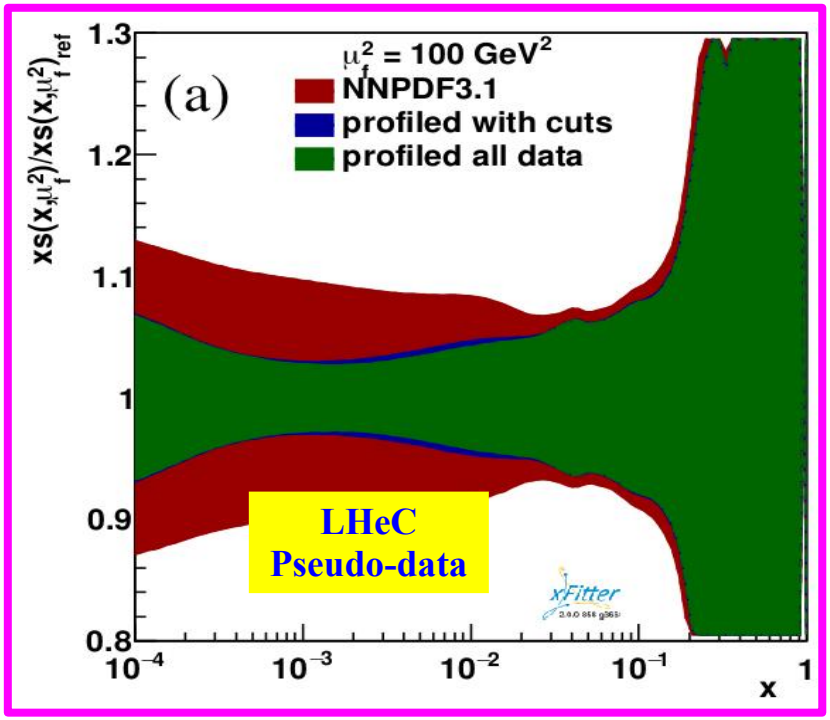


Strange PDF from LHC Measurement



$$\frac{s+\bar{s}}{\bar{u}+\bar{d}} > 1$$





significant improvement

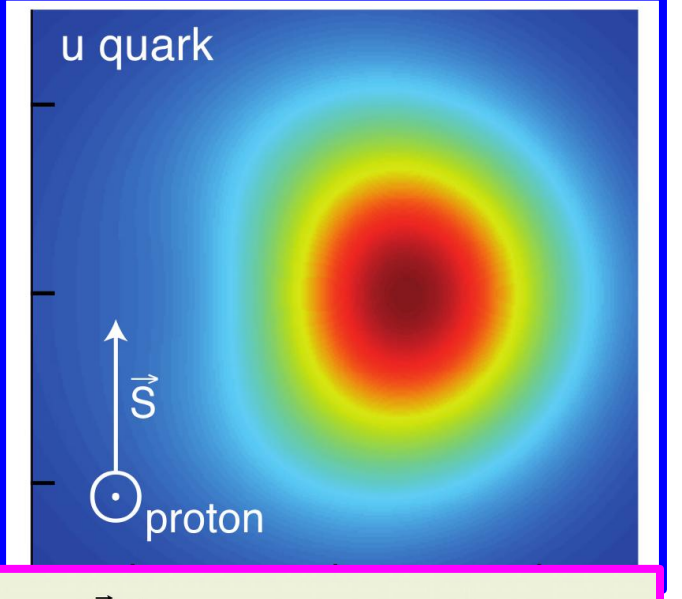
xFitter Developers' Team;
arXiv:1907.01014 [hep-ph]

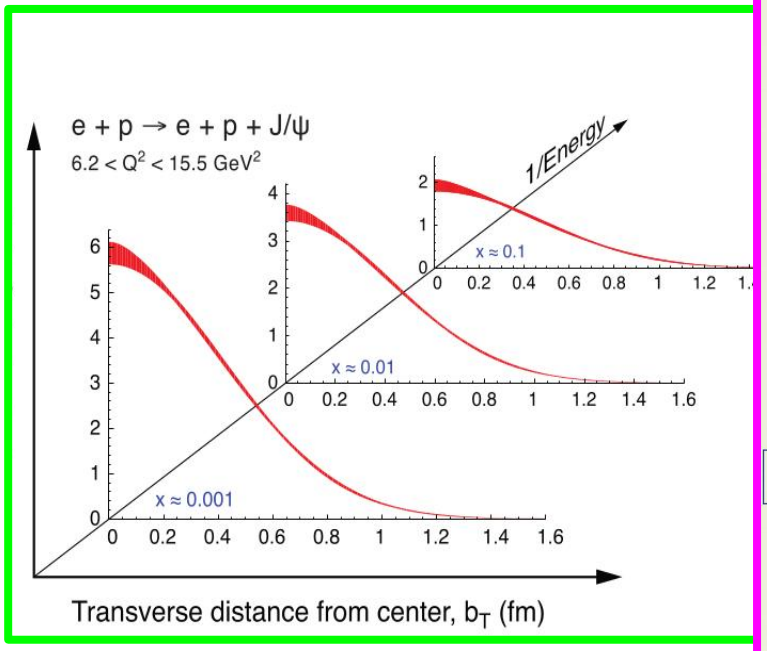
xFitter

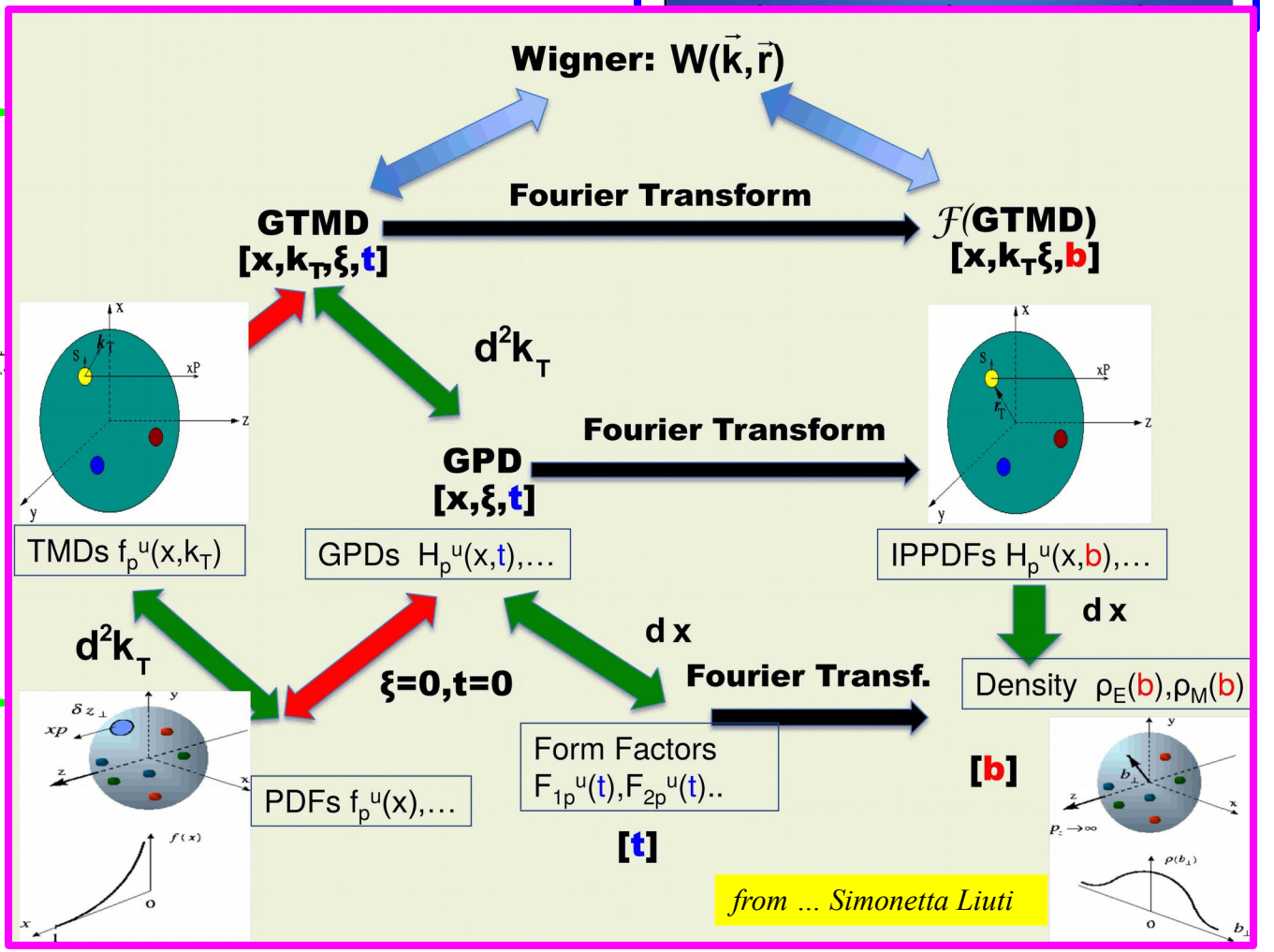
Do it yourself!!!
Try **xFitter**

… what about the Generalized PDFs …

GPDs, TMDs







Conclusions

2019 xFitter Workshop

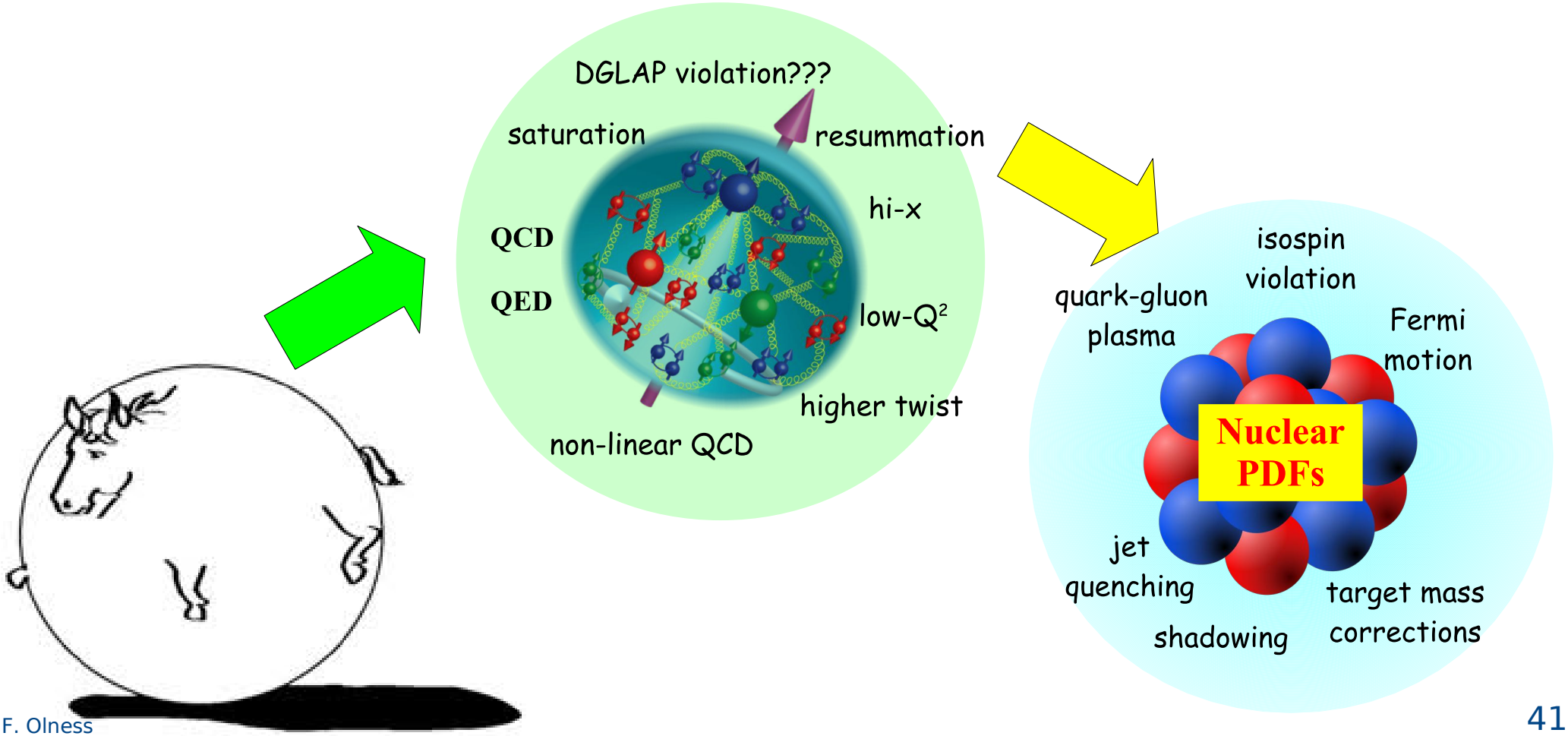
nCTEQ
& friends

DIS *an ideal QCD Laboratory*

"QCD is our most perfect physical theory" ***Frank Wilczek***

"EIC would unlock scientific mysteries" ***NAP Report***

Ideally suited to " ... glean the fundamental insights into QCD"



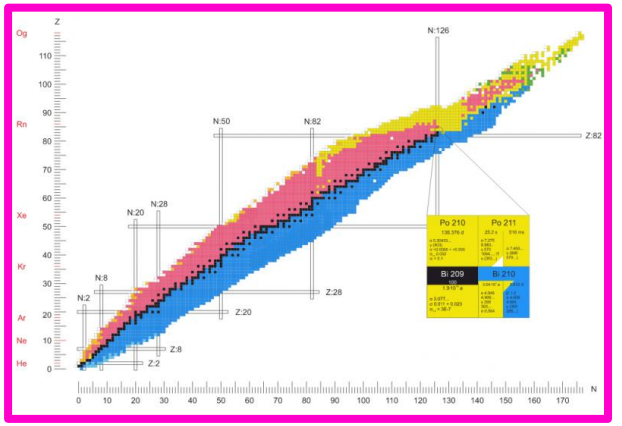
What are the challenges & opportunities

It will have high statistics for a wide variety of NUCLEI

Nuclear corrections are inextricably linked to the PDF flavor differentiation

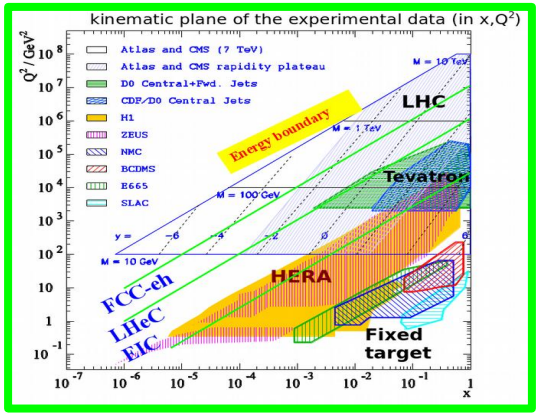
It allows us to push to HI-X

W cuts eliminate much of this region
Higher-twist, factorization violations, …
Test models in x→1 limit, e.g., d/u, …



It allows us to push to low Q

Q cuts eliminate much of this region
Explores the parton/hadron transition
Study non-perturbative collective phenomena



Nuclear PDF

The Ingredients

Mechanics of nPDFs

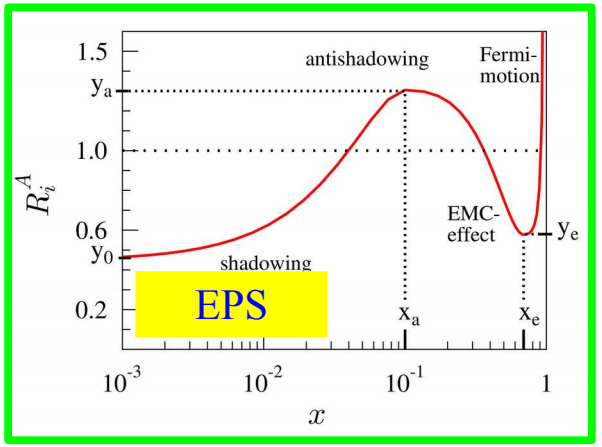
1) Multiplicative nuclear correction factors (HKN, EPPS, DSSZ)

$$f_i^{p/A}(x_N, Q_0) = R_i(x_N, Q_0, A)\; f_i^{free\ proton}(x_N, Q_0)$$

... for example

HKN

$$R_i(x, Q_0, A) = 1 + \left(1 - \frac{1}{A^\alpha}\right) \frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^{\beta_i}}$$



2) Generalized A-parameterization (nCTEQ)

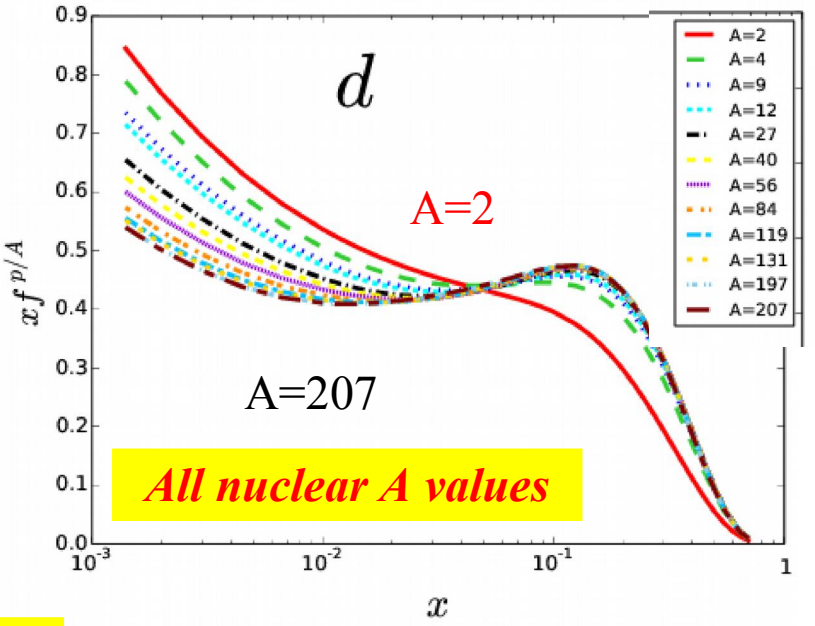
$$f_i^{p/A}(x_N, \mu_0) = f_i(x_N, A, \mu_0)$$

$$f \sim \ldots x^{c_1(A)}(1-x)^{c_2(A)}\ldots$$

$$c_k \sim c_{k,0} + c_{k,1}\left(1 - A^{-c_{k,2}}\right)$$

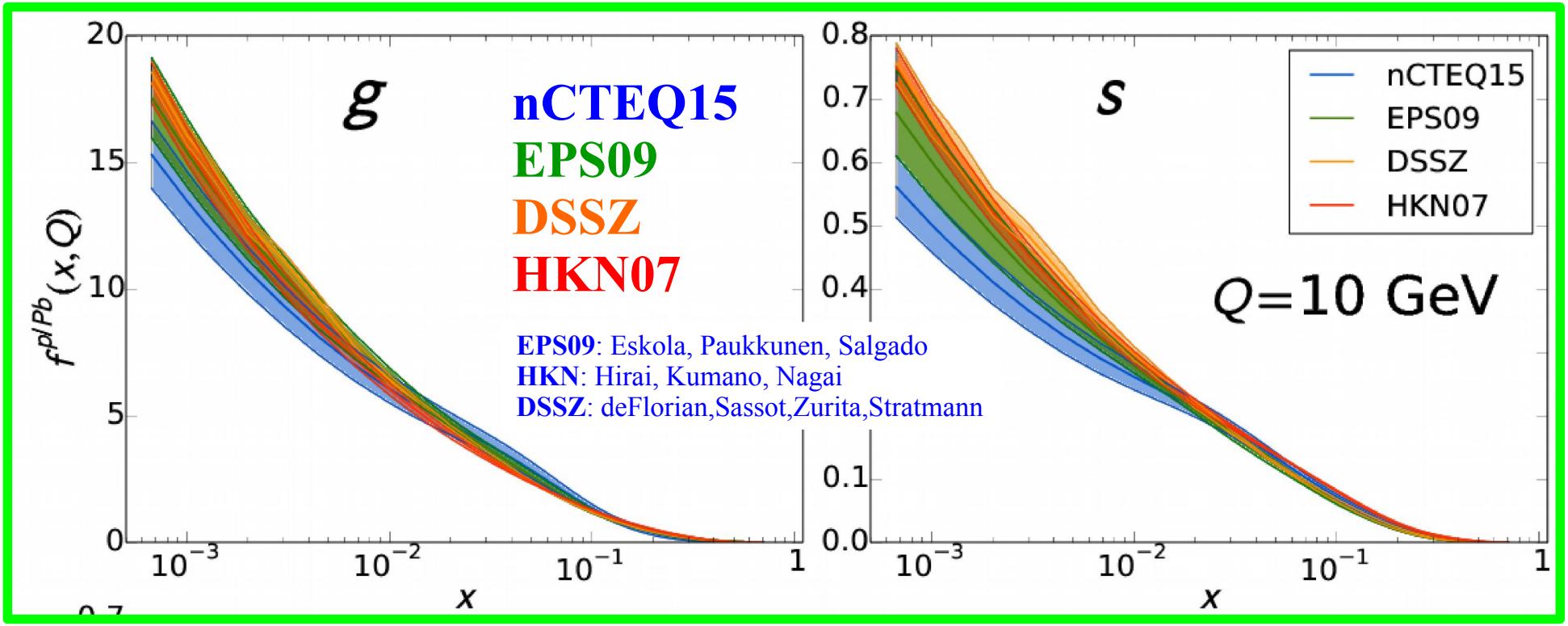
Proton

Nuclear



use proton as a Boundary Condition

Nuclear PDFs: Complementary efforts in general agreement

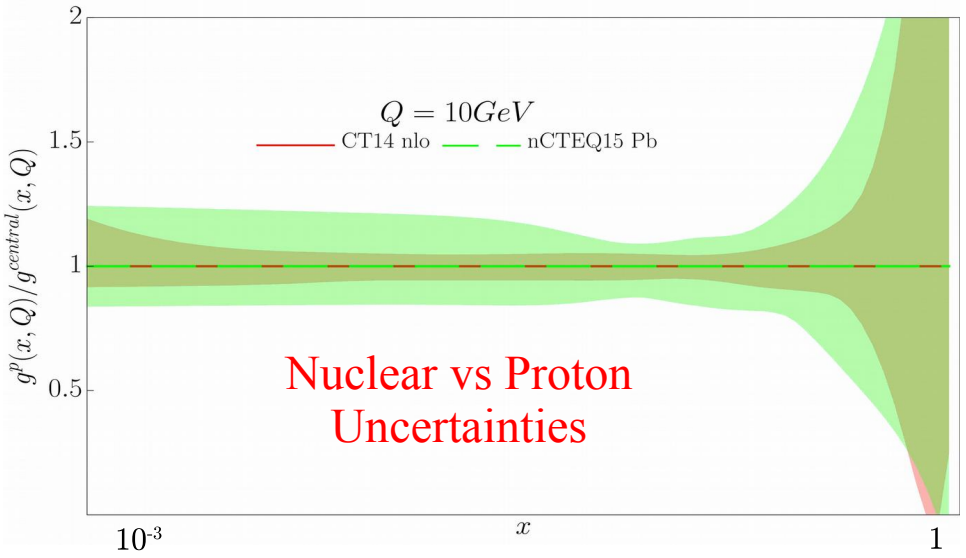


Nuclear PDFs are more complex

more DOF than Proton case

more "issues" to consider

more work to do ...



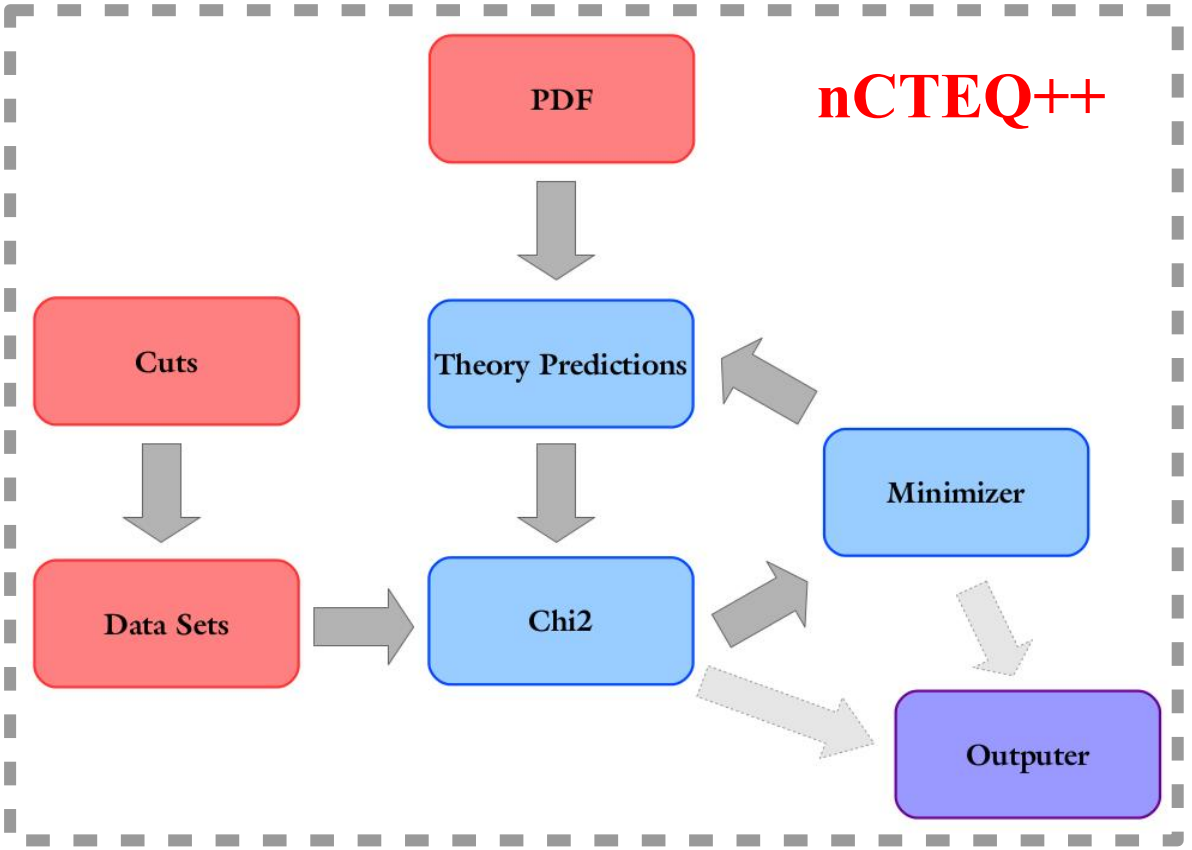
XXVIII International Workshop on Deep Inelastic Scattering and Related Subjects

Include W/Z Heavy Ion Data in fit *p-Pb*

With new tools we can now fit this data: nCTEQ++

nCTEQ++

- A complete rewrite of the nCTEQ FORTRAN fitting code in C++
- Changed the code to allow for modules when building a PDF
  - Evolution
  - Interpolation
  - Parameterization
- **Use external programs**
  - **Minuit**
  - **HOPPET**
  - **MCFM**
  - **APPLgrid**



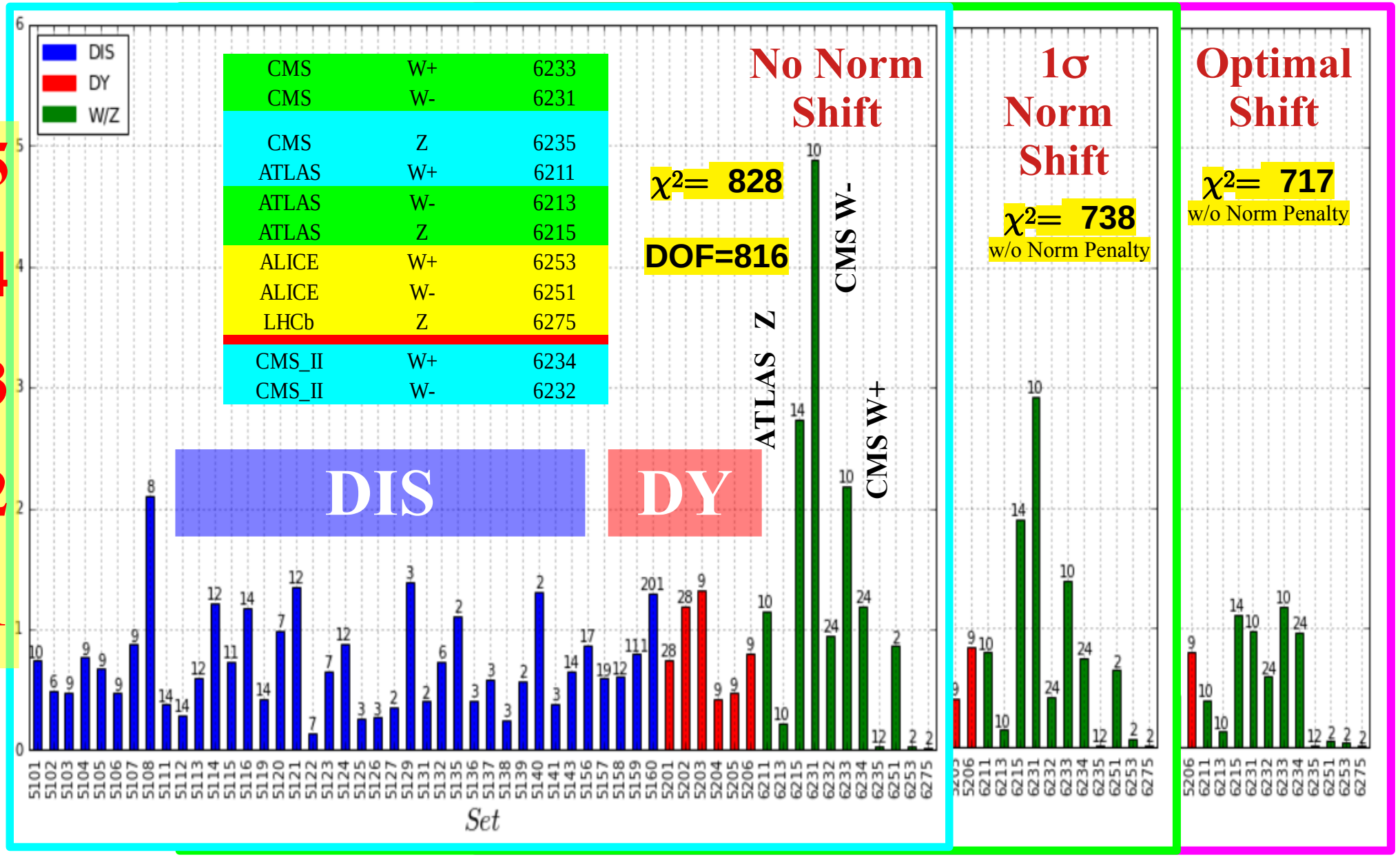
Special thanks to:
Florian Lyonnet
Tomas Jezo
Aleksander Kusina

W/Z Data in fit: LHC p-Pb

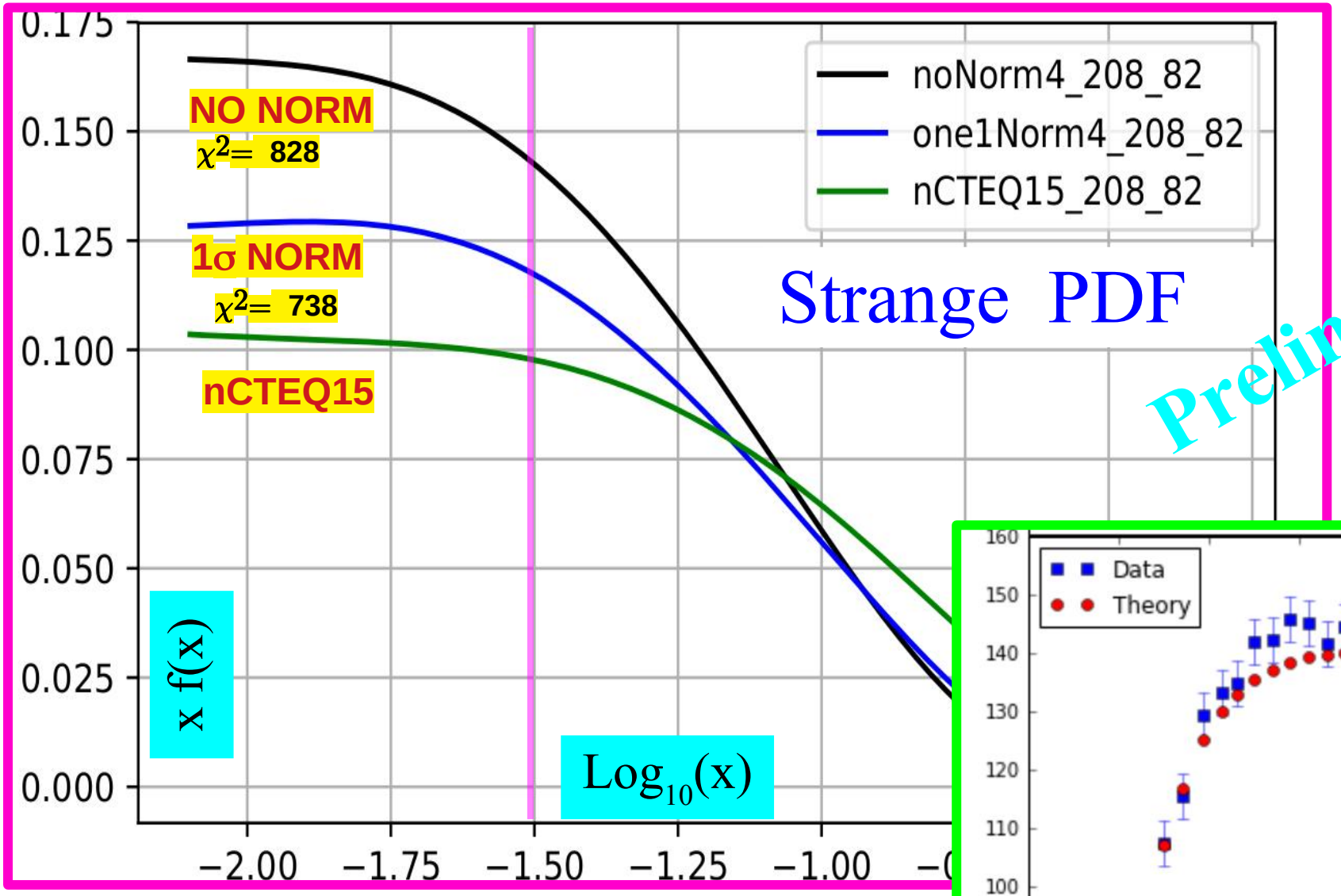
nCTEQ++

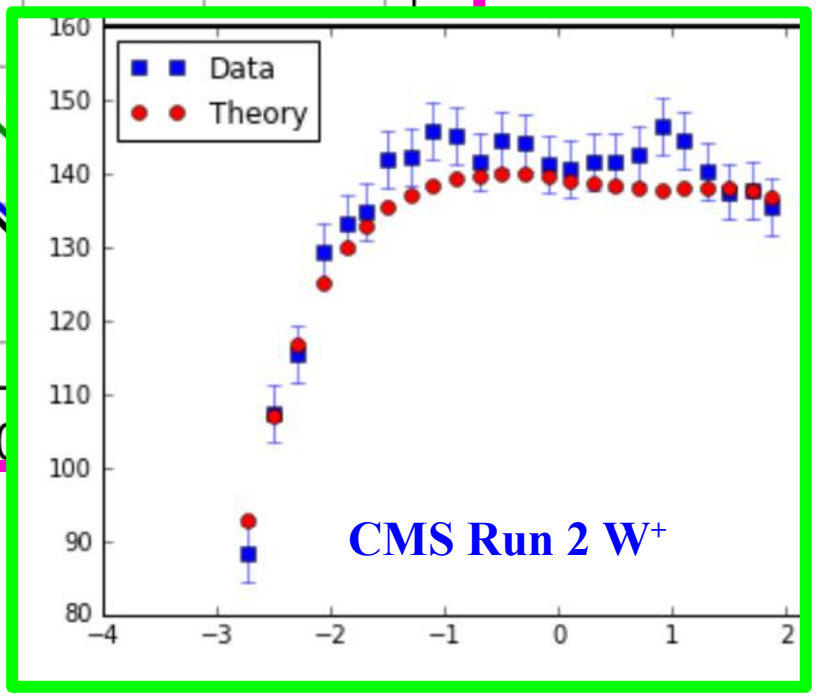
χ^2/dof

χ^2: 992 → 828

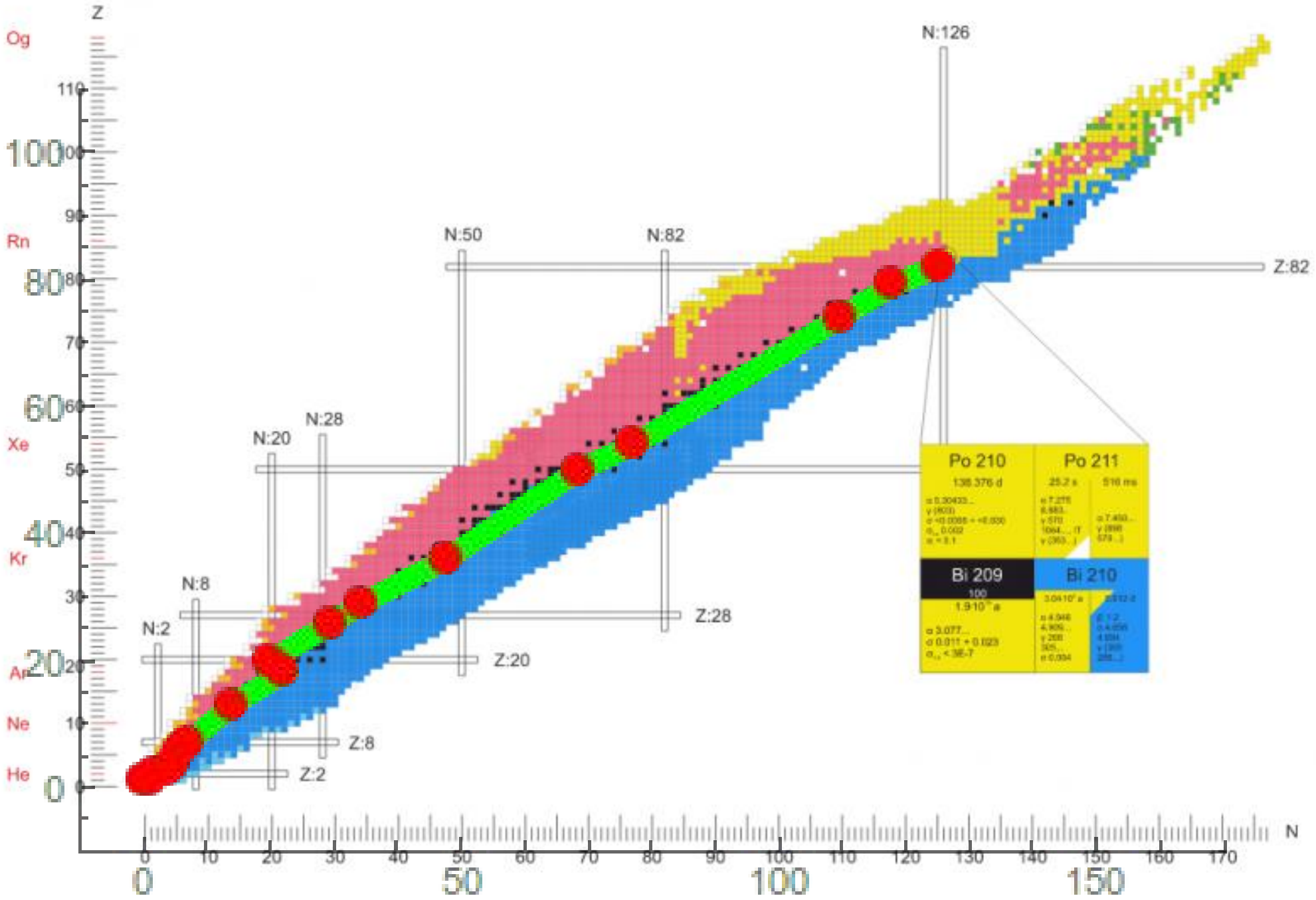


W/Z Data in fit: LHC p-Pb





Is the strange PDF driving the data ….
Or is the data driving the strange ???


Z
Og
Rn
Xe
Kr
Ar
Ne
He
N:126
N:50
N:82
Z:82
N:28
N:20
N:8
N:2
Z:28
Z:20
Z:8
Z:2
Po 210
138.376 d
Po 211
25.2 s
Bi 209
100
1.9·10^19 a
Bi 210
N
0
50
100
150

DIS at DUNE

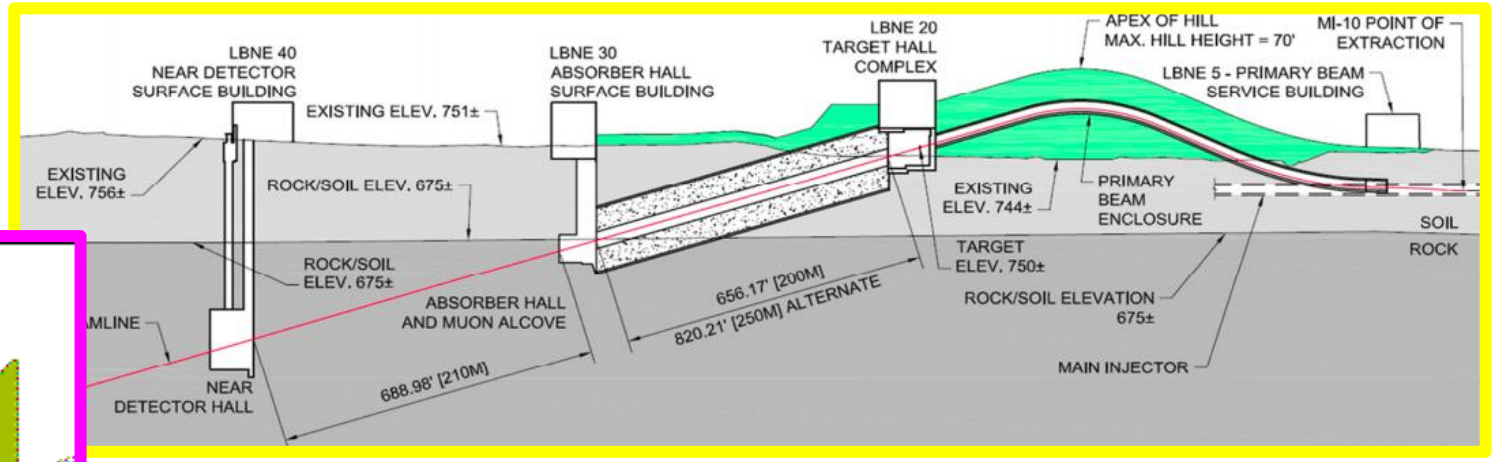
Extract νH from C and CH2 targets:

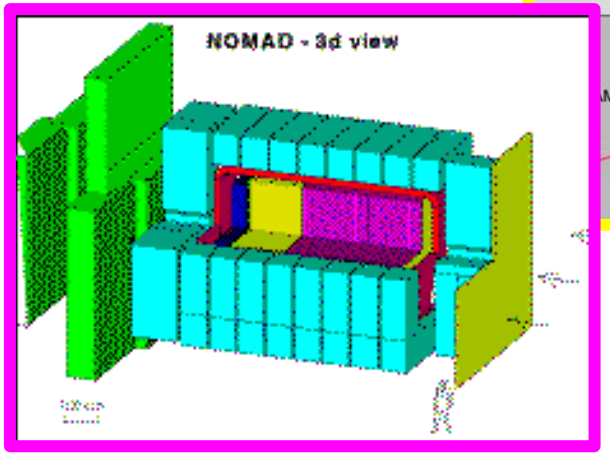
$$\nu H \rightarrow \ell^{\pm} X$$

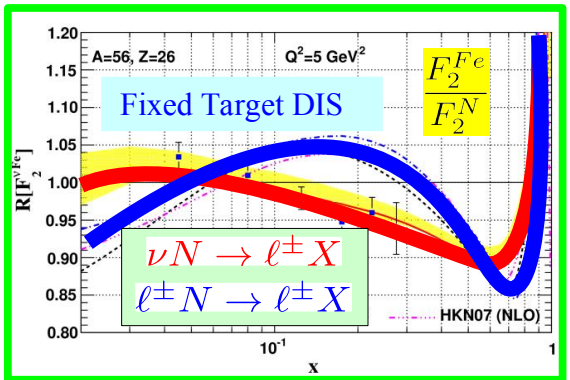
EPPSU 2020 Contribution

Enhancing the LBNF/DUNE Physics Program

P. Bernardini[1], S. Bertolucci[2], M. Bhattacharjee[3], B. Bhuyan[3], S. Biagi[11], A. Caminata[13], A. Cervelli[6], S. Davini[13], S. Di Domizio[13], L. Di Noto[13], M. Diwan[4], C. Distefano[11], H. Duyang[5], F. Ferraro[13], A. Gabrielli[2], M. Guerzoni[6], B. Guo[5], M.A. Iliescu[12,14], G. Laurenti[6], G. Mandrioli[6], N. Mauri[2], S.R. Mishra[5], N. Moggi[2], A. Montanari[6], M. Pallavicini[13], L. Pasqualini[2], L. Patrizii[6], R. Petti[5],* M. Pozzato[6], P. Sapienza[11], F. H. Sawy[7], G. Sirri[6], L. Stanco[8], A. Surdo[9], M. Tenti[10], F. Terranova[10], G. Testera[13], M. Torti[10], N. Tosi[6], R. Travaglini[6], and S. Zucchelli[2]







See Presentation by R. Petti
Wednesday WG7